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- melt pool depth
- melt dwell time and length,
- bond interface cooling rate and
- through-thickness elastic modulus

within the tape and substrate at various process speeds analytically. The predicted development of a thermal skin layer at high speeds is described *quantitatively*. An analysis of the known bonding mechanisms reveals that at a certain magnitude the thermal skin effect will influence the weld strength, by affecting the macroscopic draping, the intimate surface contact development and autohesion.

Experiments with a novel test setup are presented, which enable the consolidation at defined temperature gradients and defined tape speeds. The setup was used for an initial investigation on the general effect of temperature gradients at a consolidation speed of 1 m/s. Two conflicting positive effects of high gradients were observed: On the one hand, the backside of the tape stays unmolten, remaining flat and smooth, which is expected to be beneficial for subsequent laydowns and for the silicon roller. On the other hand, the high gradients inhibit the melt flow and malleability of the tape, due to a more narrow melt pool and a higher stiffness: Surface steps of 60 µm were thick enough to prevent the filling of a 2 mm-wide area at the edge of the step change, although the original tape had a thick and smooth surface polymer layer.

In order to control the thermal state within the tape – independently from the process speed – several irradiation strategies are investigated and compared on their usefulness and feasibility to be applied in tape placement systems. The most feasible strategy was found to be adaptive irradiation *lengths*, created e.g. by VCSEL or by electro-mechanical zoom homogenizers. The correlation between irradiation length, laser power, surface temperature and thermal penetration is described by use of the analytical solutions. Optimization potentials for the laser technologies are presented.

Finally, a novel optimization strategy for laser-assisted tape placement processes is derived with the goal of adjusting the *melt dwell length* relative to the *available pressuring length* of the respective consolidation roller, by changing the *laser irradiation length* properly.

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Thermal Skin Effect in Laser-Assisted Tape Placement
of Thermoplastic Composites

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Thermischer Skineffekt beim Laserunterstützten Tapelegen von thermoplastischen Faserverbundkunststoffen

Von der Fakultät für Maschinenwesen
der Rheinisch-Westfälischen Technischen Hochschule Aachen
zur Erlangung des akademischen Grades eines
Doktors der Ingenieurwissenschaften
genehmigte Dissertation

vorgelegt von

Thomas Weiler

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Vorwort:

Die vorliegende Dissertation entstand neben meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Aachener Zentrum für integrativen Leichtbau AZL sowie am Fraunhofer-Institut für Produktionstechnologie IPT in Aachen.

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Contents

Inhaltsverzeichnis

1	Introduction.....	1
1.1	Motivation.....	3
1.2	Parts made from UD-Fiber-Reinforced Thermoplastic Tapes	4
1.3	In-Situ Consolidation Strategy	6
1.4	Laser-Assisted Tape Placement with In-Situ Consolidation	9
1.5	Economical Relevance of the Process Speed.....	10
1.6	Topic of the Thesis	12
2	State of the Art.....	15
2.1	Tape Placement Systems with Locally Adjustable Irradiation	15
2.1.1	Laser Beam Angle.....	15
2.1.2	Laser Spot Width and Spot Height.....	17
2.1.3	Individual Tape Irradiation	19
2.1.4	Laser Intensity Distributions	20
2.1.5	Interim Conclusion	23
2.2	Application and Benefits of Adjustable Laser Irradiation	26
2.2.1	Avoidance of Unnecessary Heating	26
2.2.2	Responds to Changing Thermal Conditions.....	28
2.2.3	Responds to Changing Optical Conditions.....	29
2.2.4	Targeted Setting of Thermal Material Conditions	31
2.2.5	Interim Conclusion	34
2.3	Temperature Measurement for Closed-Loop Controls	35
2.4	Weld Strengths at Increased Process Speeds	37
2.5	Through-Thickness Temperature Distribution	39
2.5.1	Determination.....	39
2.5.2	Effect of Process Speed.....	40
2.5.3	Effect on the Placement Process	41
2.6	Conclusions from the State of the Art.....	41
3	Objectives, Tasks and Outline.....	43
3.1	Objectives and Tasks	43
3.2	Outline.....	46
4	Determination of the Temperature Distribution in Through-Thickness Direction	47
4.1	Description of the Heat Transfer Problem	48
4.2	(Detailed) Thermal Model with Numerical Solution	51
4.3	(Simplified) Thermal Model with Analytical Solutions	53
4.3.1	Derivation of the Assumptions Made.....	53
4.3.2	Description of the Simplified Model.....	60
4.3.3	Analytical Solutions	61

4.3.4	Heating Process.....	61
4.3.5	Cooling Process.....	65
4.4	Qualification by Comparisons between Model Complexities	67
5	Investigations on the Effect of Process Speed on the Through-Thickness Temperature Distribution	71
5.1	Temperature Gradients at Increased Process Speeds and their Decay during Cooling	71
5.1.1	Investigation by Use of Simplified Model and Analytical Solutions.....	71
5.1.2	Investigation by Use of Detailed Model and Numerical Solution	75
5.2	Heating Characteristic of Tape Thicknesses / Process Speeds	79
5.3	Description of the Temperature Gradient / Heat Soak.....	81
5.4	Experimental Investigations	82
5.5	Melt Pool Depth.....	89
5.6	Melt Pool Dwell Time and Length.....	93
5.7	Bond Interface Cooling Rate	95
5.8	Elastic Modulus within the Tape	95
6	Impact of the Thermal Skin Effect on the Placement Process	97
6.1	Interpretation of the Results for High-Speed Tape Placement	97
6.1.1	Effect on the Tape Plasticity.....	98
6.1.2	Effect on the Development of Intimate Surface Contact.....	100
6.1.3	Effect on Autohesion	103
6.1.4	Effect on Weld Strength Formation	104
6.1.5	Effect on Reconsolidation and Post Healing	106
6.1.6	Effect on the Crystallinity in the Bond Interface.....	106
6.1.7	Further Secondary Effects	109
6.2	Experimental Investigations	110
6.2.1	Experimental Setup (Pull-Through Test)	110
6.2.2	Experimental Design and Execution	115
6.2.3	Results of the Lap Shear Test.....	119
6.2.4	Investigation of the Fractured Surfaces.....	121
6.2.5	Interpretation and Consequence of the Results	123
7	Analysis of Irradiation Strategies for a Controlled Through-Thickness Temperature Distribution	125
7.1	Strategy 1: Maximization of the Surface Temperature	127
7.2	Strategy 2: Adaptation of Irradiation Time (~Length).....	128
7.3	Strategy 3: Decaying Laser Intensity Distribution.....	130
7.4	Concluding Evaluation.....	131
8	Speed-Adaptive Control of the Temperature Gradient by Adaption of the Heating Length.....	133
8.1	Open-Loop Control of Temperature Gradients.....	134
8.2	Closed-Loop Control of Temperature Gradients	136

8.3 Interim Conclusion	137
9 Winding Machine Concepts for a Speed-Adaptive Control of the Temperature Distribution	139
9.1 Winding Machine Concept with VCSEL	139
9.2 Winding Machine Concept with Zoom Homogenizer Optic	141
10 Optimization Strategy for the Melt Dwell Length	143
11 Summary and Outlook	147
12 References	155
13 Appendix I: Method of Mirroring Heat Sources.....	173
14 Appendix II: Pros and Cons of Increasing Temperature Gradients	175
15 Appendix III: Experimental Setups.....	177
15.1 Experimental Setup for Measurement of Temperature Gradients	177
15.2 Magnification of the Pull-Through Test.....	178
15.3 Lap Shear Test Setup	179
15.4 Reference Probe	179
16 Appendix IV: Preliminary Investigations	181
16.1 Preliminary Investigation on Surface Irradiation Homogeneity	181
16.2 Pre-Study on the Influence of Conduction in Fiber Direction.....	182
16.3 Preliminary Investigations for the Pull-Through Experiment.....	183
16.3.1 Pressure Distribution of the Consolidation Roller on the Tape	183
16.3.2 Predetermination of the Actual Nip Point Temperature	183
17 Appendix V: Equipment Used	185
17.1 Laser Technology.....	185
17.2 Holder for Laser Positioning	185
17.3 Temperature Sensors.....	186
18 Appendix VI: Material Properties.....	187
18.1 PEEK/CF.....	187
18.2 HDPE/GF	188
18.3 Surface Roughness of the HDPE/GF Tapes	189
19 Appendix VII: Extended Thermal Material Properties.....	191
19.1 Specific Heat Capacity, Enthalpy of Fusion and Crystallization	191
19.2 Temperature-Dependent Flexural Modulus.....	193
19.3 Temperature-Dependent Thermal Conductivity	194
19.4 Averaged Radiative Heat Transfer Coefficient	194
19.5 Line-Speed-Dependent Convective Heat Transfer Coefficient at Various Heating Lengths	195

20 Appendix VIII: Material Properties reg. Bonding.....	197
20.1 Reptation/Welding Time as Function of Temperature for PEEK	197
20.2 Intimate Surface Contact Development as a Function of Pressure and Surface Roughness.....	197
20.3 Temperature-Dependent Viscosity of PEEK/CF and PEEK	198
20.4 Degradation Temperature of PEEK.....	199
21 Appendix IX: Visualizations.....	201
21.1 Geometrical Sizes in Heating of Tapes by Means of Laser.....	201
21.2 Geometry and Material Conditions near the Tape Surface	202
21.3 Probe Preparations	203

Formula Symbols and Abbreviations

Formelzeichen und Abkürzungsverzeichnis

Latin symbols, capital letters

A_L	mm ²	Irradiated surface area
D_{Ah}	-	Degree of autohesion [0...1]
D_B	-	Degree of bonding [0...1]
D_{IC}	-	Degree of intimate surface contact [0...1]
E	N/mm ²	Elastic modulus
E_{1kg}	J or Ws	Consumed thermal energy for 1 kg placed tape
E_R	N/mm ²	Elastic modulus of the roller
E_a	J/(K·mol)	Activation energy: 67300 J/(K·mol)
E_f	N/mm ²	Flexural modulus
F_{App}	N	Applied (cylinder) force for consolidation
F_f	N	Breaking force during destructive testing
F_m	N	Applied testing force
Fo	-	Fourier number
G	m/s ²	Gravitational acceleration: 9.832 m/s ²
I_L	W/mm ²	Laser radiation intensity (or irradiance)
$I_L(x)$	W/mm ²	Intensity distribution in feed direction
I_{rot}	kg·m ²	Moment of inertia (or rotary inertia)
$K_{\Delta T_{calc}}$	-	Calculated ratio between surface (front side) and backside temperature
$K_{\Delta T_m}$	-	Measured ratio between surface (front side) and backside temperature
$K_{\Delta T}$	-	Temperature ratio surface(front side)-to-backside
$L_{m_{cryst.}}$	J/kg	Latent heat of crystallization
$L_{m_{melting}}$	J/kg	Latent heat of fusion
N_p	-	Number of tapes placed in parallel
N_s	-	Number of tapes placed in sequence
P	N/mm ²	Pressure or vacuum
P_{App}	N/mm ²	Applied pressure for consolidation

P_L	W	Laser source power
Q	J or Ws	Heat (energy)
$\dot{Q}$	W	Heat flow (rate of heat transfer)
$\dot{Q}_{cond}$	W or J/s	Heat flow by conduction
$\dot{Q}_{conv}$	W or J/s	Heat flow by convection
$\dot{Q}_{mold}$	W or J/s	Heat flow to mold
$\dot{Q}_{rad}$	W or J/s	Heat flow by radiation
$\dot{Q}_{roller}$	W or J/s	Heat flow to roller
R	K/W	Thermal resistance (inverse of thermal conductance)
R	J/(K·mol)	Universal gas constant: 8.31451 J/(K·mol)
R^*	-	“Lumped” proportional coefficient to describe the effect of the surface roughness for D_{IC}
R_L	K/W	(Hypothetical) thermal resistance laser-to-surface
R_a	μm	Average peak-to-valley height of surface roughness
R_{conv}	K/W	Thermal resistance by convection
$R_{conv-rad}$	K/W	Thermal resistance of radiation/convection combined
$R_{inter-layer}$	K/W	Thermal resistance in between laid tape layers
R_{mold}	K/W	Thermal resistance from tape to the mold
R_{out}	K/W	Thermal resistance to the environment
R_{rad}	K/W	Thermal resistance by radiation
R_{roller}	K/W	Thermal resistance from tape to the roller
R_{within}	K/W	Thermal resistance from one to the other body side
R_z	μm	Average surface roughness
T	°C	Temperature
$T_{surface_{actual}}$	°C	Actually prevailing surface temperature
$T_{surface_{cplx}}$	°C	Predicted surface temperature of the detailed model
$T_{surface_{final}}$	°C	Final surface temperature after the passing the heating (or irradiation) zone
$T_{surface_m}$	°C	Measured surface temperature
$T_{surface_{set}}$	°C	Setpoint for the surface temperature control system (desired value)
$T_{surface_{spld}}$	°C	Predicted surface temperature of the simplified model

T_0	°C	Ambient temperature ($\approx 20^\circ\text{C}$)
T_P	°C	Recommended processing temperature
T_{bfana}	°C	Bond interface temperature, analytical approximation
T_{bfnum}	°C	Bond interface temperature, numerical simulation
$T_{backside}$	°C	Backside temperature
T_{bf}	°C	Bond interface temperature
$T_{cryst.}$	°C	(Re-)crystallization temperature
$T_{degradation}$	°C	Temperature of definite thermal decomposition
$T_{grad}(z)$	°C/mm	Location-dependent temperature gradient
T_i	°C	Initial temperature (mostly = T_0)
$T_{melting}$	°C	Melting temperature of the polymer matrix
$T_{pyrometer}$	°C	Lowest detectable temperature of pyrometer, 74°C
T_{solid}	°C	Temperature of a surrounding solid (mold or roller)
$T_{surface}$	°C	Surface (front side) temperature of the body
T_{tape}	°C	Temperature at some position within the tape
$\Delta T_{control}$	°C	Temperature deviation of the control system
$\Delta T_{s \rightarrow b}$	°C	Temperature difference between body surface (front side) and backside
$\Delta T_{tape \rightarrow 0}$	°C	Temperature difference between some position within the tape and the environment
V_m	-	Fiber volume fraction

Latin symbols, lower-case letters

a	-	Absorptance
$a_{pull_{min}}$	mm	Minimum required acceleration
c_p	J/(kg·K)	Specific heat capacity
$c_p(T)$	J/(kg·K)	Temperature-dependent specific heat capacity
d	mm	Thickness of the body
d_{pi}	μm	Thickness of the Polyimide tape
d_R	mm	Diameter of the consolidation roller
d_{tape}	mm	Tape thickness

$\bar{h}_{conv}$	W/(m ² ·K)	Averaged convection coefficient
$h_{conv}(v_P, x_L)$	W/(m ² ·K)	Speed- and length-dependent convection coefficient
$\bar{h}_{mold}$	W/(m ² ·K)	Averaged heat transfer coefficient tape-to-mold
$\bar{h}_{rad}$	W/(m ² ·K)	Averaged radiation coefficient
$h_{rad}(T)$	W/(m ² ·K)	Temperature-dependent radiation coefficient
$\bar{h}_{roller}$	W/(m ² ·K)	Averaged heat transfer coefficient tape-to-roller
$k(T)$	W/(m·K)	Temperature-dependent thermal conductivity
$\bar{k}$	W/(m·K)	Average thermal conductivity
k_x	W/(m·K)	Thermal conductivity in fiber direction
k_y	W/(m·K)	Thermal conductivity in width direction
k_z	W/(m·K)	Thermal conductivity in through-thickness direction z
k_{zy}	W/(m·K)	Thermal conductivity in z and y direction
l_{bow}	mm	Length of loose tape in the pull-through experiment
m	kg	Mass
$\dot{q}_0$	W/mm ²	Surface heat flux
$\dot{q}_0(x)$	W/mm ²	Surface heat flux in feed (fiber) direction
$\dot{q}_0(z)$	W/mm ²	Heat flux in thickness direction (penetrating laser)
$\dot{q}_{conv}$	W/mm ²	Heat flux out of the body by convection
$\dot{q}_{in}$	W/mm ²	Heat flux into the body
$\dot{q}_{inter-body}$	W/mm ²	Heat flux between tape and substrate after contact
$\dot{q}_{out}$	W/mm ²	Heat flux out of the body
$\dot{q}_{rad}$	W/mm ²	Heat flux out of the body by radiation
r	J/(kg·s)	Heat source term for crystallization
t	s	Time
Δt	s	Time steps in the through-thickness domain
t_{App}	ms	Duration of applied consolidation pressure
t_C	ms	Cooling time (from the nip point on)
t_L	s	Irradiation time (= heating time)
t_P	s	Considered time span (in cooling analysis)
$t_W(T)$	ms	Temperature-dependent time to complete autohesion

t_f	s	Considered time span (in time-dependent modelling of the degree of bonding)
t_{melt}	ms	Melt pool dwell time
$t_{non-productive}$	s	Non-productive machine time; summed up duration tape is not placed
$t_{placement}$	s	Actual time tape is being placed
t_{pull}	s	Duration the heated weld zone moves to the nip point
$v_{P_{quasi}}$	mm/s	Quasi process speed, derived from irradiation time and the considered quasi irradiation length
v_P	mm/s	Process speed (= line speed, tape speed, substrate surface speed, placement rate)
w_L	mm	Irradiated width (mostly = w_{tape})
w_{probe}	mm	Width of the probe after trimming
w_{tape}	mm	Tape width
x	mm	Distance in feed (fiber) direction
$x_{L_{quasi}}$	mm	Quasi irradiated length
x_{melt}	mm	Melt pool dwell length
x_{pull}	mm	Distance from the heating zone to the nip point
x_{weld}	mm	Width of the bond zone of the probe
y	mm	Distance in width direction
z	mm	Distance in through-thickness direction

Greek symbols

α	m ² /s	Thermal diffusivity
α_L	°	Laser beam angle (measured relative to the substrate)
δ_L	μm	Laser penetration depth
δ_{melt}	μm	Melt pool depth
δ_{therm}	μm	Thermal penetration depth
ε	-	Emissivity
$\mu_0(T)$	Pa·s	Temperature-dependent (zero-shear rate) viscosity
ρ	kg/m ³	Density
σ	W/(m ² ·K ⁴)	Stefan-Boltzmann constant: 5.67·10 ⁻⁸ W/(m ² ·K ⁴)

τ	-	Transmittance
τ_s	N/mm ²	Shear strength
τ_{weld}	N/mm ²	Weld strength
φ_{min}	rad	Minimum required angular acceleration

Abbreviations

AFPT	Advanced Fibre Placement Technology GmbH
CAD	Computer-aided design
CCM	(Semi-) continuous compression molding
CF	Carbon fiber
C-FRP	Carbon-fiber-reinforced plastic
CNC	Computerized numerical control
CO ₂	Carbon dioxide (laser)
GF	Glass fiber
HDPE	High-density polyethylene
HSS	High-strength steel
ICT	Fraunhofer Institute for Chemical Technology
IPT	Fraunhofer Institute for Production Technology
ILSS	Interlaminar shear strength
IPT	Fraunhofer Institute for Production Technology
Nd:YAG	Neodymium-doped yttrium aluminium garnet (laser)
OOA	Out-of-autoclave (manufacturing)
PA 12	Polyamid 12
PA 6	Polyamid 6
PEEK	Polyetheretherketon
PPS	Polyphenylensulfid
SBS	Short beam bending strength
UD	Unidirectional
VCSEL	Vertical-Cavity Surface-Emitting Laser

Summary

The thesis at hand presents thermal models to predict the temperature development in laser-assisted thermoplastic tape placement processes. A focus is placed on the time-dependent through-thickness temperature distribution at increased speeds. The thermal models make it possible to obtain the:

- 1) melt pool depth,
- 2) melt dwell time and length,
- 3) bond interface cooling rate and
- 4) through-thickness elastic modulus

within the tape and substrate at various process speeds.

The formerly predicted development of a thermal skin layer at high speeds is described *quantitatively*. An analysis of the known bonding mechanisms reveals that the thermal skin effect will at some point inevitably begin to influence the weld strength, by affecting the macroscopic draping, the intimate surface contact development and autohesion.

Experiments with a novel test setup are presented, which enable the consolidation at defined temperature gradients and defined tape speeds. The setup was used for an initial investigation on the general effect of temperature gradients at a consolidation speed of 1 m/s. Two conflicting positive effects of high gradients were observed: On the one hand, the backside of the tape stays solid (not molten), remaining flat and smooth, which is expected to be beneficial for subsequent laydowns and for the silicon roller. On the other hand, the high gradients inhibit the melt flow and malleability of the tape, due to a more narrow melt pool and higher stiffness: Surface steps of 60 μm were thick enough to prevent the filling of a 2 mm-wide area at the edge of the step change. This will have a significant influence on the mechanical properties of the final part.

In order to control the thermal state within the tape – independently from the process speed – several irradiation strategies are investigated and compared on their usefulness and feasibility to be applied in tape placement systems. *Maximization* of the surface temperature was found to be easy to implement, but also limited, because the degradation temperature of the respective polymer sets a barrier. Changing the irradiation *distribution* promises the most benefits and widest field to control $T(z, t)$, but is expected to be more difficult to realize with state-of-the-art laser system technologies and today's (not inverse) heat transfer simulation tools. The most feasible strategy was found to be adaptive irradiation *lengths*, either created e.g. by VCSEL or by electromechanical zoom homogenizers. The correlation between irradiation length, laser power, surface temperature and thermal penetration is described by use of the analytical solutions. Optimization potentials for the laser technologies are presented.

Finally, a novel optimization strategy for laser-assisted tape placement processes is derived with the goal of adjusting the *melt dwell time* relative to the *available pressuring time* of the respective consolidation roller, by changing the *laser irradiation length* properly.

Zusammenfassung

In der vorliegenden Arbeit wurden Modelle zur Beschreibung der laserunterstützten Erwärmung von faserverstärkten Thermoplastbändern vorgestellt. Der Fokus lag auf der zeitabhängigen (transienten) Temperaturentwicklung in der Dickenrichtung des Materials bei hohen Geschwindigkeiten. Durch die thermischen Modelle war es möglich die folgenden Größen in Abhängigkeit zur Geschwindigkeit zu setzen:

- 1) Schmelzbad-Tiefe,
- 2) Schmelzbadverbleib-Zeit und -Länge,
- 3) Abkühlrate der Fügezone und
- 4) der Elastizitätsmodul in Dickenrichtung.

Das vorhergesagte Entstehen einer dünnen thermischen Hautschicht von GROUVE konnte erstmalig *quantitativ* beschrieben werden und eine Analyse der Fügemechanismen zeigte, dass dieser thermische Skineffekt zwangsläufig auch die Fügefestigkeit beeinflussen wird, durch entweder eine Beeinflussung der makroskopischen Drapierung, des intimen Lagenkontaktes oder der Autohäsion.

Ein neu entwickelter Prüfstand erlaubte eine erste Untersuchung zum generellen Einfluss von Temperaturgradienten bei Konsolidierungsgeschwindigkeiten von 1 m/s. Zwei (unerwartete) im Konflikt stehende positive Effekte wurden beobachtet: Auf der einen Seite bleibt das Tape bei hohen Temperaturgradienten auf der Rückseite im festen Zustand (nicht geschmolzen), was sehr wahrscheinlich positiv für nachfolgende Konsolidierungsprozesse ist, aufgrund der geringen Rauigkeit und weil die elastische Rolle thermisch geschont wird. Auf der anderen Seite verringert ein hoher Temperaturgradient das verfügbare Schmelzbad und die Formbarkeit des Tapes nimmt ab: Ein Dickensprung auf der Oberfläche von 60 μm – induziert durch ein Polyimid-Tape – reichte aus, um das Füllen einer 2 mm breiten Zone am Rand des Dickensprungs zu verhindern. Es ist zu erwarten, dass dieses Phänomen sich entscheidend auf die Bauteileigenschaften auswirkt, da Tape gelegte Oberflächen i.d.R. Kavitäten von $> 200 \mu\text{m}$ aufweisen, bspw. an Tape-Kreuzungspunkten oder -Überlappungen/-Lücken.

Um den thermischen Zustand im Material maschinell zu steuern – unabhängig von der Prozessgeschwindigkeit – wurden verschiedene Bestrahlungsstrategien betrachtet und auf deren Nutzbarkeit und Einsetzbarkeit in Tapelegesystemen hin verglichen: Als vielversprechende mittelfristige Strategie lässt sich die Anpassung der Bestrahlungslänge nennen. Der zu deren Nutzung relevante Zusammenhang zwischen Bestrahlungslänge, Laserleistung, Oberflächentemperatur und thermischer Eindringtiefe wurde durch analytische Lösungen beschrieben und visualisiert.

Zum Schluss wurde eine neue Optimierungsstrategie für laserunterstützte Tapelegeprozesse abgeleitet. Bei dieser Strategie wird versucht, die Schmelzbadverbleib-Zeit relativ zu der verfügbaren Druckzeit der Konsolidierungsrolle anzupassen, durch eine entsprechende Anpassung der Bestrahlungslänge.

1 Introduction

Einleitung

1.1 Motivation

Motivation

Humanity is becoming more mobile. The reasons for this are developing economies, growing global value chains and international tourism. The *World Economic Forum* has collected driving forces behind mobility and their related negative impacts (Table 1.1). At the same time, the world's population is growing at a rate of about 1% per year. The growth is predicted to slow down to 0.1% by 2100. This still means that within this century, the number of people on the planet will further grow to 11.2 billion, according to [ROSE17] – a population of 3.8 billion more people than today.

Table 1.1: Driving forces for mobility and its rising negative impacts [WEF17]

Triebkräfte der Mobilität und deren steigende negativen Auswirkungen

Driving forces		Rising negative impacts
<i>Economic</i>	Developing economies	Climate change by CO ₂
	Global value chains	Air pollution by smog
	Growing intern. business	Health issues
<i>Non-Economic</i>	Freedom and adventure	Conflicts over energy sources
	War and crisis / migration	Shortage of resources
	Urbanization	
	International education	

While the **automobile market** in North America, Europe and Japan has come to a stable size (in terms of automobiles sold per year), the emerging markets of Brazil, Eastern Europe, China and India are expected to grow consistently during the next two decades, driven by millions of people entering the middle class [MOHR13] [PWC16]. The **aerospace sector** is expected to grow at even faster rates: According to the company Airbus, air travel will *double* in the next 15 years. A potential of 32,500 airplane deliveries is expected during the course of the next 20 years [FLAI16, p. 2].

This growing demand for mass transportation causes a large amount of the global **fossil fuel consumption** (oil and gas). Roughly 30% of the overall energy consumption in the United States in 2016 was caused by the **transportation sector** [LLNL15]. The growing fuel consumption leads to rising negative consequences for humankind: A changing global climate by greenhouse gases (CO₂) [MCGR17], air pollution in cities by smog [CHAN07], health issues and conflicts over energy sources.

Enabling the transportation of people/goods with fewer resources will likely become a key challenge in the 21st century. Besides the development of alternative drive technologies and energy storage systems, building vehicles *lighter* is a key approach to decrease the energy consumption and emissions in the future. The physics behind

this are well described in vehicle engineering handbooks, e.g. in [FRIE13, p. 31-33].

Various lightweight materials have been developed in the recent decades and are commercially available. However, a prerequisite for the widespread application of any material is the industry's capability to transform the material into valuable products, at reasonable costs and in high production numbers. Quality has to be ensured, especially in safety-critical lightweight products (e.g. in those of Figure 1.1 and Figure 1.2). These challenges are further complicated by the trend towards *mass customization* (or *individualized production*), because the batch numbers of common parts are decreasing. Traditional economy-of-scale effects for cost reduction do not apply here [KULL15, p. 36].

Future lightweight production systems must be able to manufacture a wider range of product designs out of a variety of materials without increasing the cost significantly. Only when these economic prerequisites can be met, the "[...] *invisible hand of the market* [SMIT76, p. 456]" can take over on its own, spreading lightweight products at a high rate, without the need for tedious legislative measures.

1.2 Parts made from UD-Fiber-Reinforced Thermoplastic Tapes

Aus unidirektional faserverstärkten Thermoplast-Tapes hergestellte Bauteile

One promising material to manufacture lightweight products economically are pre-impregnated unidirectional(UD)-fiber-reinforced thermoplastic tapes. These tapes are made of thousands of micrometer wide fibers per square millimeter (Figure 1.1), which give the material its high strength and stiffness per weight. The mechanisms behind the "strengthening effect" of fibers are well described in [SCHU07, p. 21-25].

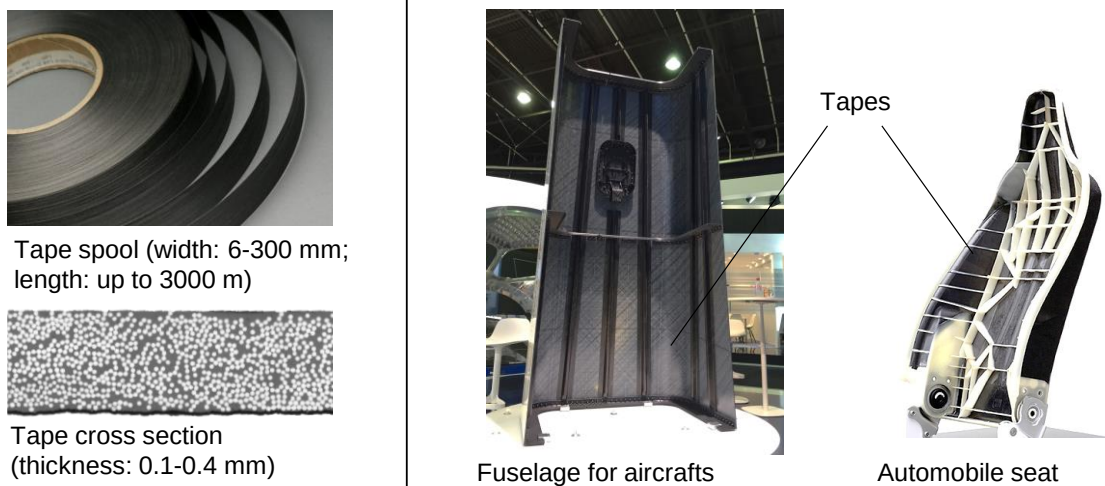


Figure 1.1: Left: Tape spool [AUTO17a] and microsection. Right: Demonstrators for the mobility industry made from UD thermoplastic tapes: Fuselage (left) [JECC17] and automobile seat (right) [DODE15]

Links: Tapespule und -querschliff. Rechts: Demonstratoren für die Mobilitäts-industrie hergestellt aus UD verstärkten Thermoplastbändern: Flugzeugrumpf (links) und Autositz (rechts)

Several processing advantages come with the fiber-embedding *thermoplastic* matrix: The material can be melted rapidly, formed or joined, as well as re-melted and re-joined; ideal properties for automated high-volume production of complex products.

Automated placement offers the possibility to position the tapes with its load-bearing fibers at the *place* and *direction* of the components' loads [FABE16, p. 6-8]. Instead of using uniform-thick textile-based sheets with pre-conditioned fiber directions, e.g. 0/90°, the parts can be made according to the loads and in non-uniform thicknesses. Cutouts can be spared, minimizing the scrap during finishing [BREC11a]. These are crucial benefits, as the material is a significant cost driver, preventing many promising lightweight products to enter mass markets – especially in the case of carbon fibers with costs of > 12 €/kg and high-temperature polymers, like Polyetheretherketon (PEEK) with > 40 €/kg, compared to < 1 €/kg for steel [LAES12] [RED14] [ASHL13].

Interestingly enough, novel lightweight products, based on thermoplastic tapes, are not only able to help saving energy in mobility, but also to exploit energy resources, previously inaccessible, helping to bridge the gap from fossil fuels to renewables. Recently introduced *flexible thermoplastic composite risers* for example, support the development of ultra-deep-water oil and gas fields in depths of > 2000 m [UMAP17]:

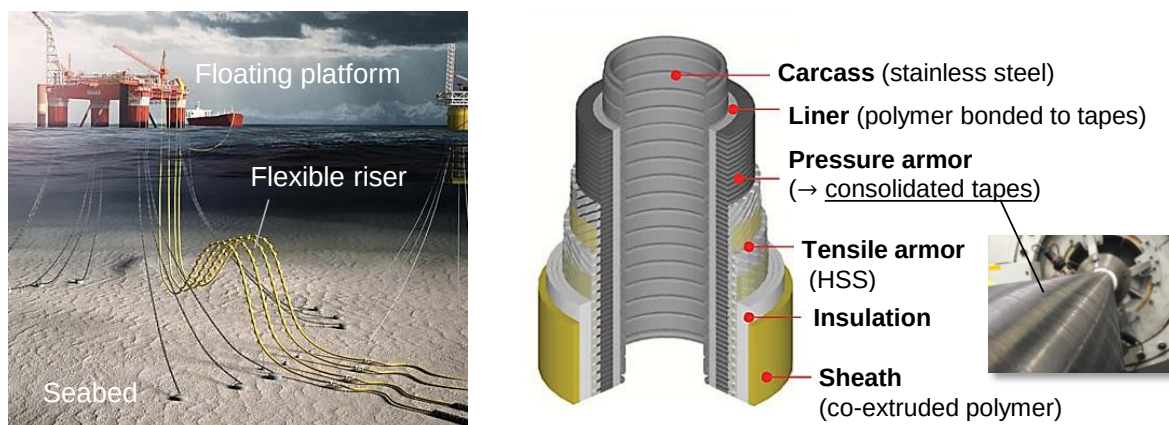


Figure 1.2: Recently qualified product for the oil and gas industry made from of UD-reinforced thermoplastic tapes by continuous in-situ tape winding: flexible riser for oil and gas production [SUBS14] [JHA14, p. 3] [CALI16]

Kürzlich zugelassenes Produkt für die Öl- und Gasindustrie hergestellt aus unidirektional faserverstärkten Thermoplastbändern durch kontinuierliches Insitu-Tapewickeln: formflexible Steigrohre zur Öl- und Gasförderung

These pipes do not only utilize the weight-specific strength of the material, but also its high elongation to break for heave compensation, low permeability and non-corrosiveness, making risky oil exploration more secure. The pipes are also spoolable (on $\varnothing > 6$ m), saving transportation footprint and costly time during offshore installation [AIRB17]. Alternative riser designs require underwater buoyancies with long installation times [BAI12, p. 874-888]. Additionally, the weight reduction of the *pressure armor* (Figure 1.2) reduces the weight load on the *tensile armor* and thereby the need for costly high-strength steel (HSS) cords – a classic upward lightweight spiral.

1.3 In-Situ Consolidation Strategy

In-situ Konsolidierungsstrategie

In order to manufacture lightweight products from UD thermoplastic tapes, three basic objectives have to be accomplished (the sequence of these processes can differ):

- (1) placement of tapes, according to the layup design
- (2) consolidation of tape layers, by heating and pressuring
- (3) forming (or draping) to the final part geometry

In the context of tape placement, the term **consolidation** is generally used to describe the *void-free bonding* of adjacent layers (Figure 1.3) [ZHAN17]. However, several individual phenomena occur during consolidation simultaneously and sequentially “[...] *like intimate contact between adjacent plies, interply adhesion, fiber deformation and movement, molecular diffusion and diffusion of volatiles* [...]” [BERS03, p. 434]. To avoid misconceptions, the term *consolidation quality* is used in this thesis as the “*lumped*” description of the *achieved weld strength*. A maximum consolidation quality is generally achieved when the weld strength *equals* the strength of the polymer.

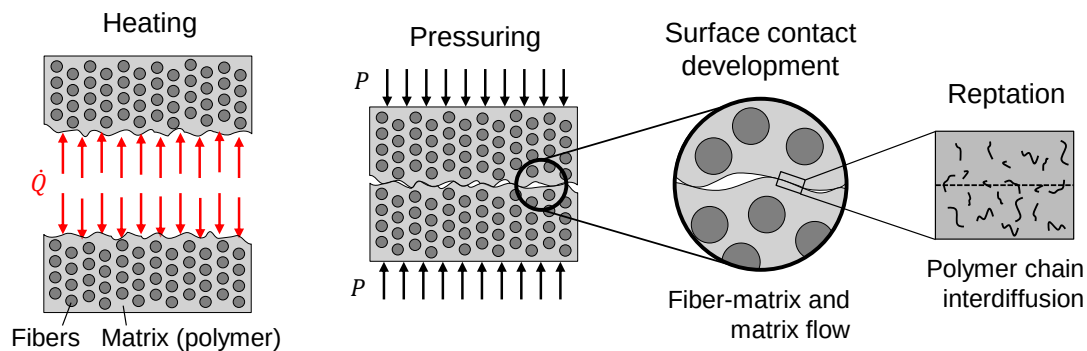


Figure 1.3: Consolidation process of fiber-reinforced thermoplastic tapes

Konsolidierungsprozess von faserverstärkten thermoplastischen Bändern

Consolidation is a crucial process step in thermoplastic composite manufacturing, as it determines the final mechanical properties of the part. It also strongly influences the economy of the final part, by the output rate and energy demand of the machine.

Two consolidation *strategies* have to be distinguished:

- (a) Post consolidation and
- (b) In-situ consolidation.

Both **strategies** are shown exemplary in Figure 1.4 for the manufacturing of a squared composite sheet. The strategies are investigated and pursued by various companies and institutes worldwide: Fraunhofer Institute for Chemical Technology (ICT) [ROCH12], Neue Materialien Fürth GmbH (NMF) [KROP17] [KUNS17], Dieffenbacher GmbH [DIEF17a], Boikon B.V. [BOIK17] for (a), and Fraunhofer Institute for Production Technology (IPT) [BREC13], AFPT GmbH [AFPT17a] and Automated Dynamics [AUTO17a] for (b). The required machine effort, cycle time and the reliability of the process strategy determine the final cost and quality of the product.

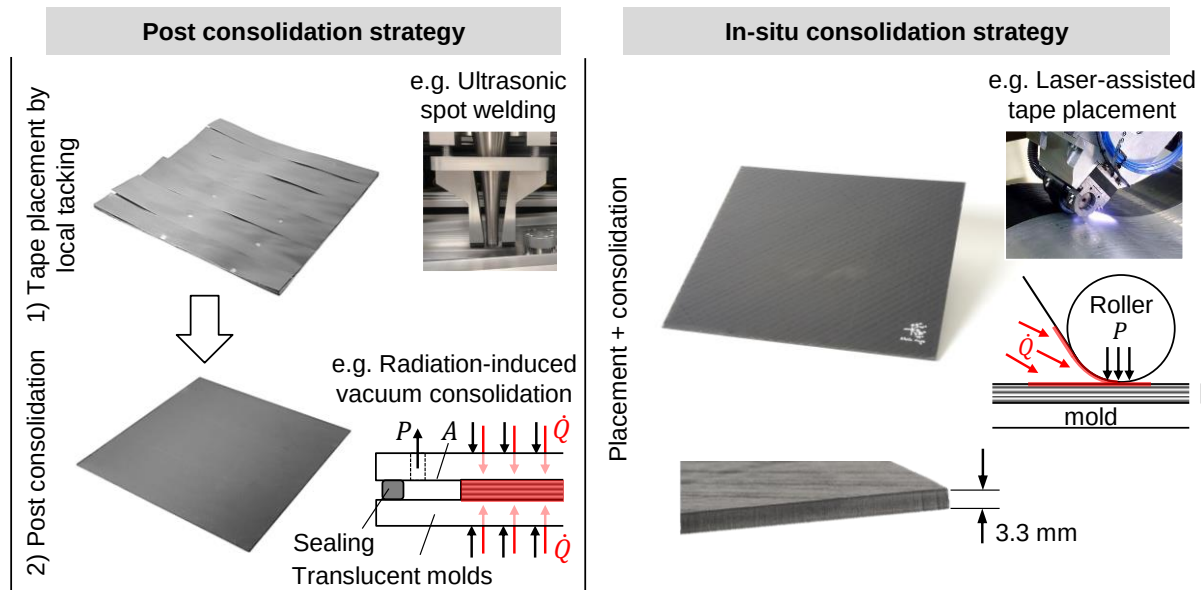


Figure 1.4: Locally tacked and post-consolidated UD thermoplastic tapes (left) [BAUM16]; in-situ consolidated UD thermoplastic tapes (right) [BREC14b, p. 2]

Lokal geheftete und nachkonsolidierte UD-Thermoplast-Tapes (links); insitu konsolidierte UD-Thermoplast-Tapes (rechts)

In case the post consolidation strategy is pursued, tapes are placed at relatively high rates, e.g. 1 tape per second in [DIEF17b], with local (or low) adhesion. The main objective is to enable subsequent handling for the post consolidation process. After placement, the unconsolidated stack is fed into additional systems, in which the stack is exposed to temperature and pressure for a certain period of time.

Autoclaves can be used to accomplish this process step, but represent investments in the millions, according to [GRUB01, p. 3] [LAMO02, p. 3]. Autoclaves require a lot of energy for the pressuring of the chamber and time for pressure build up is high. The product output per time unit per capital investment (kg/hr/€) is therefore rather low.

Due to these reasons, **out-of-autoclave manufacturing (OOA)** has been pursued by many authors [BROS14]. The presented **radiation-induced vacuum consolidation** in Figure 1.4 (left-hand side) is able to avoid the autoclave by use of a local vacuum within a translucent mold. The mold is transparent for infrared radiation and is coated with a special silicon layer to avoid polymer adhesion. The consolidation pressure can exceed the barometric pressure (≈ 1 bar) of conventional vacuum-assisted methods by increasing the internal mold surface accordingly. Fast cooling is achieved by forced convection or by water spraying. [BAUM16] The system is a significant improvement to the classical autoclave. However, the output remains comparably low (roughly 1 pc/min) and is currently limited to structures of homogeneous thickness.

Double-belt presses can also be utilized to accomplish consolidation. The machines offer relatively high output rates, due to the continuous operation. High pressure rates of up to 80 bar, high temperatures of up to 400°C and (mechanical) speeds of up to 48 m/min can be realized [GEIG17]. The material can be molten prior to the pressuring fields in preheating modules, e.g. continuous infrared ovens. However, the pre-product

has to be uniformly thick for the use of double-belt presses to achieve a homogeneous pressure distribution. Isobaric double-belt presses further require a closed surface of the pre-product, to avoid local pressure drops or leakage of the pressuring media (oil/air) [SAND09, p. 27-30] [HELD17] [HYMM17]; near-net shaping is not possible. The investment cost of double-belt presses are in the millions [OSTG97, p. 29].

The more recently introduced **continuous compression molding (CCM)** machines combine tape placement, forming and consolidation in one process step by intermitted match-die molding. Relatively high output rates can be achieved (40 m/hr) [GARD10]. The process is used commercially by the company xperion [XPER17]. However, geometries are limited to 2.5 dimensional shapes; cutouts lead to higher material cost.

Lastly, post consolidation can be achieved during **press forming**, with assistance by **injection molding** pressure, but also creates technical difficulties: First of all, flooding of the whole part surface with pressurized melt is often not allowed by the part design. The high injection pressures of up to 1000 bar can lead to unintentional fiber displacements, if the laminate is not well pre-consolidated. Achieving complete consolidation by the 1-d closing stroke alone is difficult, especially at high mold draft angles. Mold tolerances or material accumulation in mold cavities make a reliable post consolidation difficult to achieve. Iterative optimization of the mold geometry is time-consuming and therefore costly; conformable molds, out of elastic materials, are not durable enough for mass manufacturing – especially at high temperatures [SCHO13].

The **in-situ strategy** pursues to place *and* consolidate tapes in *one process step*, by local melting with high-power heat sources and subsequent pressuring with flexible or rigid rollers; consolidation speeds of > 1 m/s have been reported [AFPT17b]. The strategy provides several beneficial features: Intermediate systems in the process chain are spared; near-net shaping and non-uniform-thickness manufacturing are both possible [KERM15] [BREC15]. The handling effort can be reduced and the energy efficiency is high, as the polymer is only locally molten. An assumed key advantage of roller-based consolidation is the direct squeeze-out of air with the roller (compare the travel lengths of trapped air in flat consolidation methods, like in [BAUM16]).

The **technological challenge** of the in-situ strategy is to ensure reproducible consolidation qualities during the entire course of the manufacturing cycle – especially at high process speeds. Parts are generally made out of a high number of individual tapes. For example, a 2 mm-thick laminate of 1 square meter, made out of 0.2 mm-thick and 25 mm-wide tapes, requires 400 (!) individual tape pieces. Inappropriate process control or unrecognized errors during manufacturing are not acceptable.

The **heating process** plays a key role for the in-situ strategy: Only when the tape is molten rapidly and repetitively, a welding process with reliable consolidation quality can be ensured. Meeting this requirement becomes most challenging at *high process speeds* and at *varying process conditions*, like changing material properties or part geometries. The previously mentioned trend towards mass customization is a growing driver behind the conflicting demands for productivity, reliability and flexibility.

1.4 Laser-Assisted Tape Placement with In-Situ Consolidation

Lasergestütztes Tapelegen mit Insitu-Konsolidierung

In order to perform thermoplastic tape placement with in-situ consolidation at high speeds, fast and controlled melting of the polymer is of utmost importance. Many **heat sources** have been investigated on their ability to achieve reliable heating rates at high speeds: hot gas torch [SCHL04a, p. 6], hot air heater, infrared heaters [SCHM05, p. 64] [BREC15, p. 11] and open flame [FUNC95] [BERE02]. Comparative summaries on heating technologies are given in [SCHL04b], [AUGU14a] and [SCHL09].

Lasers offer four distinctive advantages: practically no heat transfer resistance at the heated surface, very low response time (< 10 ms) for precise temperature control, high energy input per time and defined areal heating by tailored optics [GROU12, p. 3].

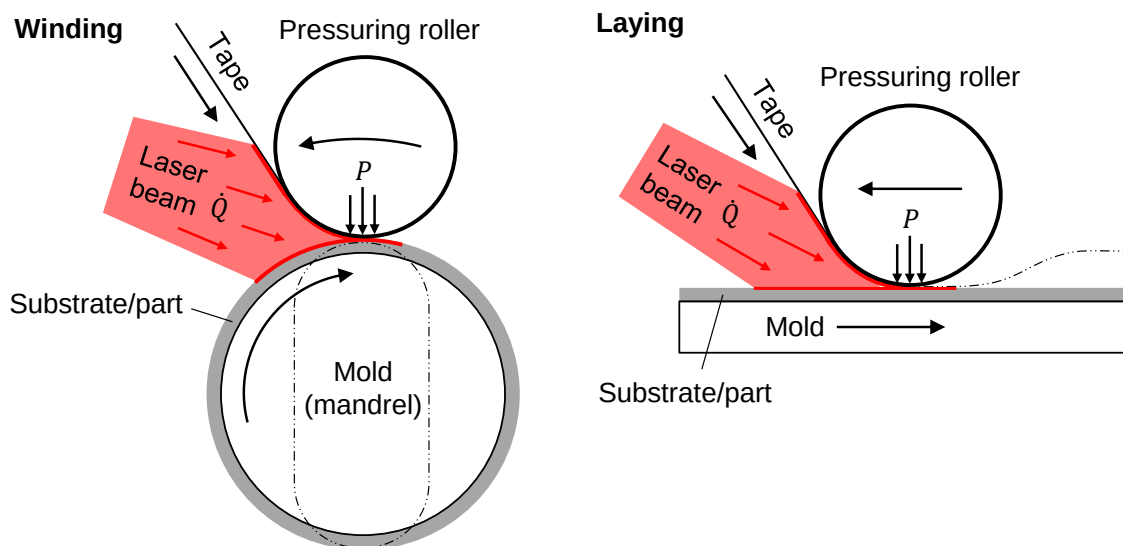


Figure 1.5: Laser-assisted placement processes: tape winding (left) and tape laying (right)
Lasergestützte Ablegeprozesse: Tapewickeln (links) und Tapelegen (rechts)

The technology is used in a wide **range of machines**, varying in the shape, size and motion of the mold. The most significant distinction can be drawn between tape *winding* and *laying*. In the case of tape winding, the mold is generally of closed shape, with a limited number of add and cut procedures; in the case of tape laying, the mold is flat or slightly curved, leading to multiple add and cut procedures. Several machine kinematics have been developed for laser-assisted tape placement.

For tape winding:

- Rotating molds with a lateral-moving placement head [AFPT17a]
- Co-rotating heads along a forward-moving substrate (e.g. pipe) [MATU17]

For tape laying:

- Driven placement heads by robots or gantry systems [FRAU15] [AFPT17a]
- Driven molds with static placement heads [BREC15] [AUTO17a]
- Synchronously driven heads and molds [GALL14] [AFPT17a]

1.5 Economical Relevance of the Process Speed

Wirtschaftliche Bedeutung der Prozessgeschwindigkeit

A key figure of any production system is its output rate; the capability to produce a high amount of parts per time unit, commonly measured in kg/hr. The output rate plays a significant role for the final part cost, because machines require capital investments and operators. Figure 1.6 illustrates the parameters to determine the output rate of a tape placement system: (a) process speed v_p , (b) tape thickness d_{tape} , (c) width w_{tape} and (d) density ρ , (e) number of parallel and (f) sequentially placed tapes N_p , N_s .

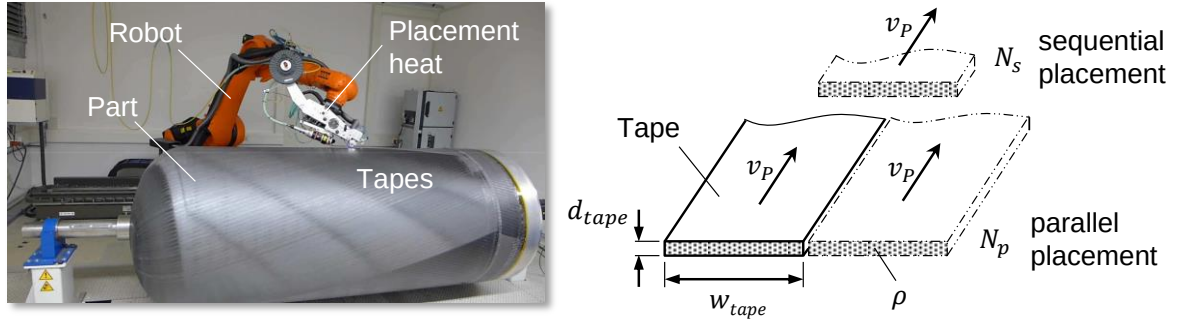


Figure 1.6: Left: Tape placement system [HENN14]; right: parameters for the determination of the output rate in thermoplastic tape placement machines

Links: Tapelegesystem; rechts: Parameter zur Ermittlung der Ausbringung beim Thermoplast-Tapelegemaschinen

The output rate of a system can be obtained by multiplication of these parameters:

$$\text{Output rate} = v_p \cdot d_{tape} \cdot w_{tape} \cdot \rho \cdot N_p \cdot N_s \cdot OPE \quad [\text{kg/hr}] \quad (1.1)$$

where OPE is the *overall process efficiency* of the system. This value is defined as the ratio of the *actual* time the tape is placed $t_{placement}$ and the *overall production time*:

$$OPE = \frac{t_{placement}}{t_{placement} + t_{non-productive}} \quad [0 \dots 1] \quad (1.2)$$

The overall production time is the sum of $t_{placement}$ and the non-productive time $t_{non-productive}$, which results from secondary processes, like head positioning, starts/stops, spool/part exchanges, machine failures and maintenance jobs.

The parameters (a) to (f) can be analyzed for their potential to be improved (Table 1.2): Increasing the thickness of the tape leads to higher output rates, but will at some point inevitably reduce the strength of the laminate, due to the reduction of the thin-ply effect [SIHN07, p. 1002] [AMAC14, p. 126]. It will also make the tapes stiffer and therefore less suitable for spooling and guiding in the placement head; from practical experience, this occurs at $d_{tape} > 0.3$ mm. Wider tapes reduce the near-net shaping efficiency [SCHU16, p. 3] [ASHA17, p. 34-36]. Only few systems are known, capable of *parallel* placement in combination with *in-situ consolidation* of thermoplastic tapes, e.g. [BREC11b]. *Sequential* tape placement is known to be only feasible in continuous winding [HAUB02] [AIRB17] [MATU17] and tape pultrusion [SUPR17].

Table 1.2: Optimization potentials of manufacturing parameters for higher output rates
Optimierungspotentiale von Fertigungsparametern für erhöhte Ausbringung

Parameter	Analysis of maximization	Exp. potential for improved output
(a) Process speed v_p	To be discussed	To be discussed
(b) Tape thickness d_{tape}	Reduces the strength of the laminate; higher bending radii inhibit spoolability/guiding	Low
(c) Tape width w_{tape}	Increases scrap rate (less near-net shaping)	Medium
(d) Tape density ρ	Predefined by tape manufacturing process	Low
(e) Number of parallel tapes placed N_p	Few <i>in-situ consolidation</i> systems available in the market, mostly continuous winding systems	High
(f) Number of sequential tapes placed N_s	Few <i>in-situ consolidation</i> systems available in the market, mostly continuous winding systems	High
(g) Overall process efficiency OPE	Defined by the specific machine attributes, availability and spool/part exchange time	Medium

The *placement speed* remains one of the key parameters to improve the output rate of the machine. The relationship of the placement speed v_p to the final part cost (€/kg) can be calculated by division of the *Annual cost* and the *Annually produced mass*:

$$Part\ cost\ per\ weight(v_p) = \frac{Annual\ cost}{Annually\ produced\ mass(v_p)} \quad (1.3)$$

The cost per part weight can be plotted (Figure 1.7), assuming 250 work days per year, machine operator cost of 50.000 €/a, 3-shift production (24 hours) and a 500.000 € tape placement machine with 5 years of depreciation. From literature analysis, the *OPE* was found to be < 0.5 in all analyzed systems [AFPT17a] [CORO17] [AUTO17a]. Energy cost are also plotted, assuming 6 kW overall power (2 kW optical, 4 kW cooling) for a 25 mm-wide tape and 250 mm/s process speed and 0.19 €/kWh. Please note that the energy demand actually decreases with higher speed, due to lower heat soaks (Figure 5.2, p. 74) and note that the machines for higher process speeds are more costly, due to higher laser investment and costs for more dynamic drive systems.

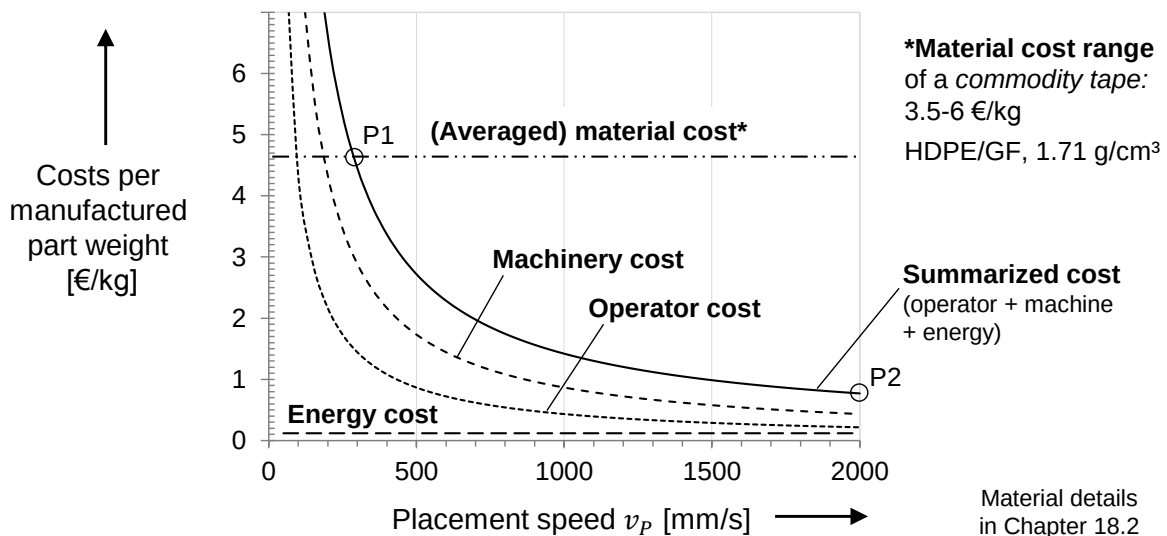


Figure 1.7: Breakdown of costs per produced part weight for various placement speeds
Kostenanteile am produzierten Bauteil je Prozessgeschwindigkeit

Economic Target Analysis. To achieve a summarized cost (incl. operator, machine and energy) per weight below the mean material cost (4.75 €/kg), the placement speed has to be at least > 275 mm/s (P1 in the diagram); reaching < 1 €/kg requires > 2000 mm/s (P2). It can be concluded:

The low volumetric laydown rate of a single tape, compared to the machine investment and operator cost (mm³/s vs. €), dominates the economy of tape placement (!) The energy demand of the heat source (laser) appears negligible.

Due to this cost structure, it is highly likely that the *process speed* will become a major *optimization target* in the future of tape placement, as it significantly influences the final part cost. This is especially relevant for the processing of cost-efficient materials, which are relevant for mass markets. Process speeds have been reported to reach > 1 m/s, but statements in the literature differ in this respect considerably [COMP14].

1.6 Topic of the Thesis

Thema dieser Arbeit

The *maximum process speed* of laser-assisted tape placement machines has often been associated with the *maximum energy density* of the implemented heat source, e.g. in [ESCH01, p. 16,18] and the *maximum dynamics* of the manipulation systems, e.g. that of 6-axis robots [KOEL08, p. 60]. Regarding state-of-the-art machines, these assumptions are plausible. However, modern laser technology does not impose any limitations here, as laser manufactures achieve powers of > 30 kW [LASE13a]; manipulation systems also have been reported to reach up to 3 m/s. Especially *tape winding* machines and *2-d tape laying* machines are capable of reaching high process speeds, due to the low magnitude of mass accelerations and recurring motion sequences [ASHA17] [AUTO17b].

The thesis in hand will deal with the question of what happens when the process speed is increased, yet the final surface temperature kept constant by increasing the laser power accordingly. A major boundary condition will therefore be the use of unlimited laser power in combination with a well-functioning surface temperature control, which have recently been shown to work within narrow tolerances [BREC16].

Previous works have focused on the computation of the *surface temperature* for *specific laser systems*, like in [SCHM94] [ESCH01] [KOEL08] [STEY13] or [STIM14]. The thermal analyses performed in these works considered already the time-dependent (transient) through-thickness temperature distribution $T(z, t)$, however only for *specific* parameters. The main research objective was the identification of the maximum process speed for a targeted surface (melting) temperature, with the applied laser source; not the temperature distribution $T(z)$ itself – and its cause and effects.

In order to predict what will happen at increasing speeds, this thesis will present novel analytical solutions for the heating and cooling phase, which extend previous works of VOR DEM ESCHÉ, STEYER, STIMPFL and KERMER-MEYER. The novel solutions are able to

consider a wide range of parameter settings in a short period of time and are capable of considering additional effects, like heat accumulation in thin tapes (and substrates).

The prediction accuracy of the solutions will undergo two qualification procedures:

- (1) comparisons with a detailed numerical model and
- (2) irradiation experiments.

Thereafter, both the analytical and the numerical solutions will be applied to analyze $T(z, t)$ for the process speed range of 50 to 4000 mm/s. The analyses will show that the required (surface) bonding temperatures can be reached far beyond 1 m/s with the available laser powers on the market, however, significant changes in the through-thickness temperature distribution $T(z)$ are the inevitable consequence → thermal skin effect.

The observed effect leads to the second major question to be discussed in this thesis: How does the thermal skin effect influence bonding preconditions, like melt pool depth, dwell time, cooling rate or tape plasticity? It will be shown how exactly these thermal values decrease/increase with higher process speeds, which in turn leads to the final question: How do the changing preconditions – e.g. a more narrow melt pool – influence the polymer bonding process in detail and which process speeds could become critical for the weld strength development?

Coming full circle, it will be discussed what

- (a) the findings mean for parameter optimizations in today's tape placement machines and
- (b) how novel (adjustable) laser irradiation technologies might be able to improve today's machines.

Customized optics for example, enable the setting of defined laser intensity profiles [KLOC17] and modern semiconductor lasers make it possible to change irradiation profiles online in microseconds [PHIL17]. Based on these recent innovations in laser technology and the lessons learned from the thermal analysis of $T(z, t)$, novel machine concepts will be presented and a novel optimization strategy for the irradiation will be proposed.

Summarizing, the thesis in hand deals with the effect of high process speeds and high laser powers on the through-thickness temperature distribution – in short: the thermal skin effect – and its impact on the bonding process.

The following state-of-the-art chapter will begin by giving an overview of tape placement systems with a focus on locally adjustable laser irradiation technologies, as this will set the basis for optimization proposals at the end of the thesis.

2 State of the Art

Stand der Technik

The state-of-the-art chapter will approach the subject from the system point of view with the implemented laser technologies in tape placement heads. The chapter will end with the known effects of the irradiation on the weld strength, in analogy to Figure 3.4 (p. 46). The first Section 2.1 will present the so-far-developed tape placement systems in evolutionary steps, from the beginnings in the '90s towards the higher irradiation flexibility of today – experimental setups are not included. The section will take a broader perspective on the subject of *adjustable irradiation* and will present its implementations in tape placement heads. Section 2.2 will show applications and benefits of adjustable irradiation for the process and Section 2.3 will present the state of the art in thermal control. The weld strength at higher process speed will be the topic of Section 2.4. Finally, in Section 2.5, the core topic of this thesis will be addressed: the through-thickness temperature distribution; how it has been determined so far, how controlled, and what is known about its correlation with the weld strength.

2.1 Tape Placement Systems with Locally Adjustable Irradiation

Tapelegesysteme mit örtlich einstellbarer Bestrahlung

This section will exclusively address tape placement *systems*. In case *process benefits* of adjustable irradiation are of interest the reader might move on to Section 2.2.

2.1.1 Laser Beam Angle

Lasereinstrahlwinkel

Flexible irradiation in tape placement systems goes back to the very first laser-assisted systems themselves. SCHMIDT presented a machine with a manual tilting mechanism that was used to adjust the energy input in tape and substrate (Figure 2.1, top left):

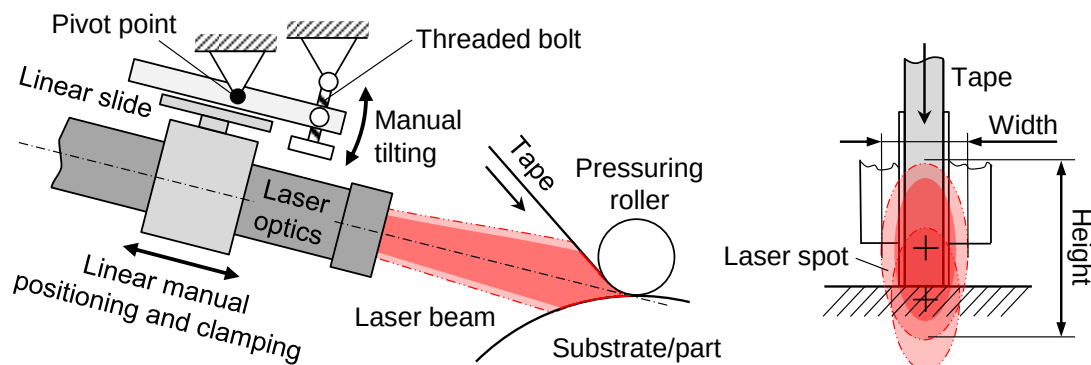


Figure 2.1: Principle for adjustable laser irradiation in laser-assisted thermoplastic tape placement systems from the year 1994; adapted from SCHMIDT [SCHM94, p. 120]
Prinzip zur gezielt einstellbaren Bestrahlung in lasergestützten Thermoplast-Tapelegesystemen aus dem Jahr 1994

The laser used was a 1600 W Nd:YAG laser with a beam shaping optic that formed an elliptical laser spot. An additional linear positioning mechanism of the optics enabled a change in the irradiated width. All posing procedures had to be done manually and did therefore not allow *online* adjustments during the manufacturing process. Further investigations with the system of SCHMIDT have not been reported. VOR DEM ESCHÉ used the same principle of tilting and linear positioning of the optic holder with a Nd:YAG laser [ESCH01, p. 56, 99]. The mechanical design differed only slightly.

KOELZER moved one technological step further and introduced an electromechanical tilting system to adjust the laser irradiation ratio between tape and substrate *automatically* [KOEL08, p. 101]. This increased the flexibility of the thermal control during the manufacturing process. The company AFPT GmbH commercialized systems with this principle [AFPT17a]. Instead of tilting the entire (diode) laser source, as KOELZER did in his initial experiments, AFPT systems enable the electromechanical tilting of a fiber-coupled optic, which reduces the moving mass and the required design space within the head [HENN14] (Figure 2.2). The Fraunhofer Institute for Production Technology (IPT) introduced several similar systems in the recent past [STEY13, p. 84] [BREC14a].

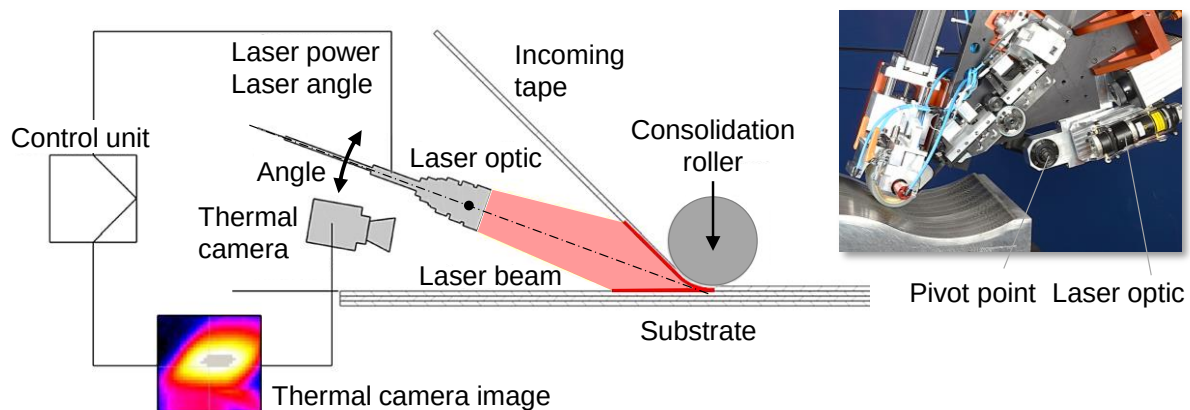


Figure 2.2: Closed-loop surface temperature control of tape and substrate by adjustment of laser angle and laser power; adapted from [HENN14] and [BREC14a, p. 52]

Regelung der Oberflächentemperatur von Tape- und Substrat über Verstellung des Lasereinstrahlwinkels und der Laserleistung

A general drawback of the laser-angle-based temperature control is the coupling of two control values – laser power and laser angle. Both do influence the surface temperature. For example, tilting the laser more towards the substrate does require increased overall laser power to keep the surface temperature of the tape at a constant level.

This interdependency of control values requires a sensitive optimization of the control parameters, to avoid instabilities and overshoots of the surface temperature [KOEL08, p. 113-118]. Systems with two independent laser sources for individual control of tape and substrate are not known (but expected to improve the control accuracy and stability.)

The company Automated Dynamics presented a (manual) tilting and fixation of the laser optics around the nip point (Figure 2.3). This is a noticeable difference, compared to the formerly presented systems, as the tilting motion results in varying irradiation angles only, rather than (significantly) varying energy inputs in tape and substrate.

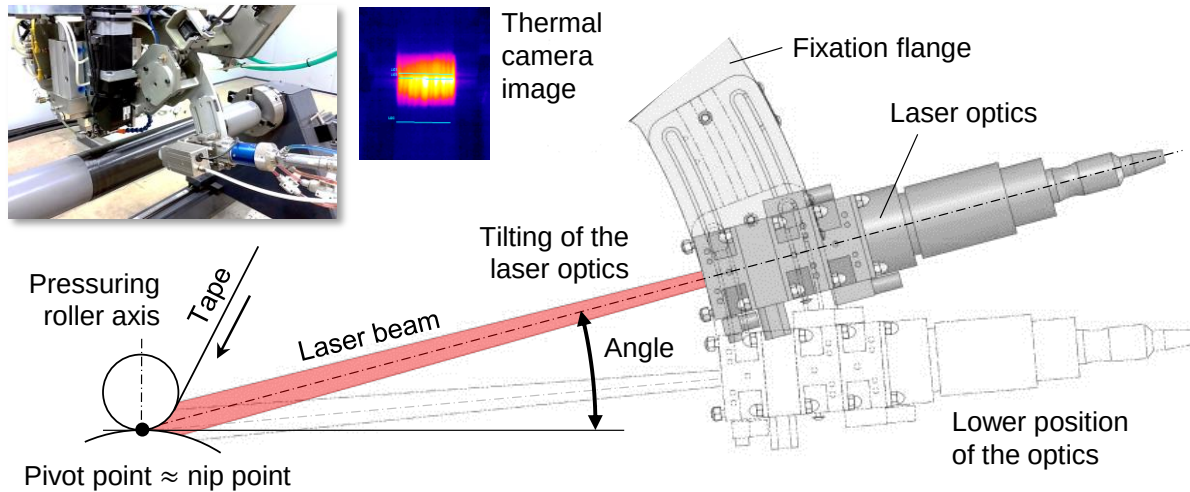


Figure 2.3: System for tilting of the laser beam around the nip point [BECK12] [AUGU15]
System zur Verkipfung des Laserstrahls um den Kontaktpunkt der Andruckrolle

This special method of tilting can also help to minimize the shadow area: In winding processes for example, the laser can be positioned perpendicular to the pressuring roller axis, leading to maximized laser beam penetration close towards the nip point. A similar system design was found in [MIKR17].

2.1.2 Laser Spot Width and Spot Height

Laserbrennfleckbreite und -höhe

The formerly described systems by SCHMIDT and VOR DEM ESCHE used *elliptical* laser spots, which had the inevitable consequence of unwanted heating left and right from the tape (Figure 2.1). KOELZER improved this state by introducing the use of homogenizer optics to shape the initial Gaussian beam into a (homogeneous) top-hat profile [KOEL08, p. 31-35]. Typical top-hat profiles are shown in Figure 2.4, next page.

In order to adjust the width of the laser spot, the systems of SCHMIDT and VOR DEM ESCHE adjusted the *distance* of the optics to the workpiece (compare Figure 2.1, p. 15). A certain *divergence* of the laser beam is a prerequisite for this method. The range of adjustment was limited [SCHM97, p. 120]. Furthermore, the spot width and height were *intertwined* in this approach. Independent setting was not possible.

Online adjustment of the laser spot has been made possible recently in two tape placement systems, presented by STIMPFL and by the company Coriolis Composites. Both use electromechanical positioning of optics in *zoom homogenizers* (Figure 2.4). The system of STIMPFL used a CO₂ laser source with a wavelength of 10.6 μm . Due to this wavelength, lenses could not be used, as the absorption would be too high. The lenses would heat up, expand and could deflect or even shatter.

The shaping of the beam was instead realized by multiple faceted mirrors, positioned relative to each other by rotational and translational piezo-electric actuators (Figure 2.4 left-hand side). The range of the spot width was 15 mm to 85 mm; that of the height was 60 mm to 100 mm. A motorized wobbling mirror was required, to blur out interference patterns, thereby homogenizing the laser intensity distribution. A stepper motor was used for the beam angle adjustment. [STIM14, p. 65-75] Due to a low amount of moving masses and use of piezo actuators, the response time of the system was rather low, compared to the former presented systems.

The CO₂ laser source required further mirrors to guide the beam from the external laser source to the moving placement head (not shown in the figure). This increased the complexity and fragility of the system. It is sensitive towards dust and mechanical disturbances. Further investigations with the system are not reported.

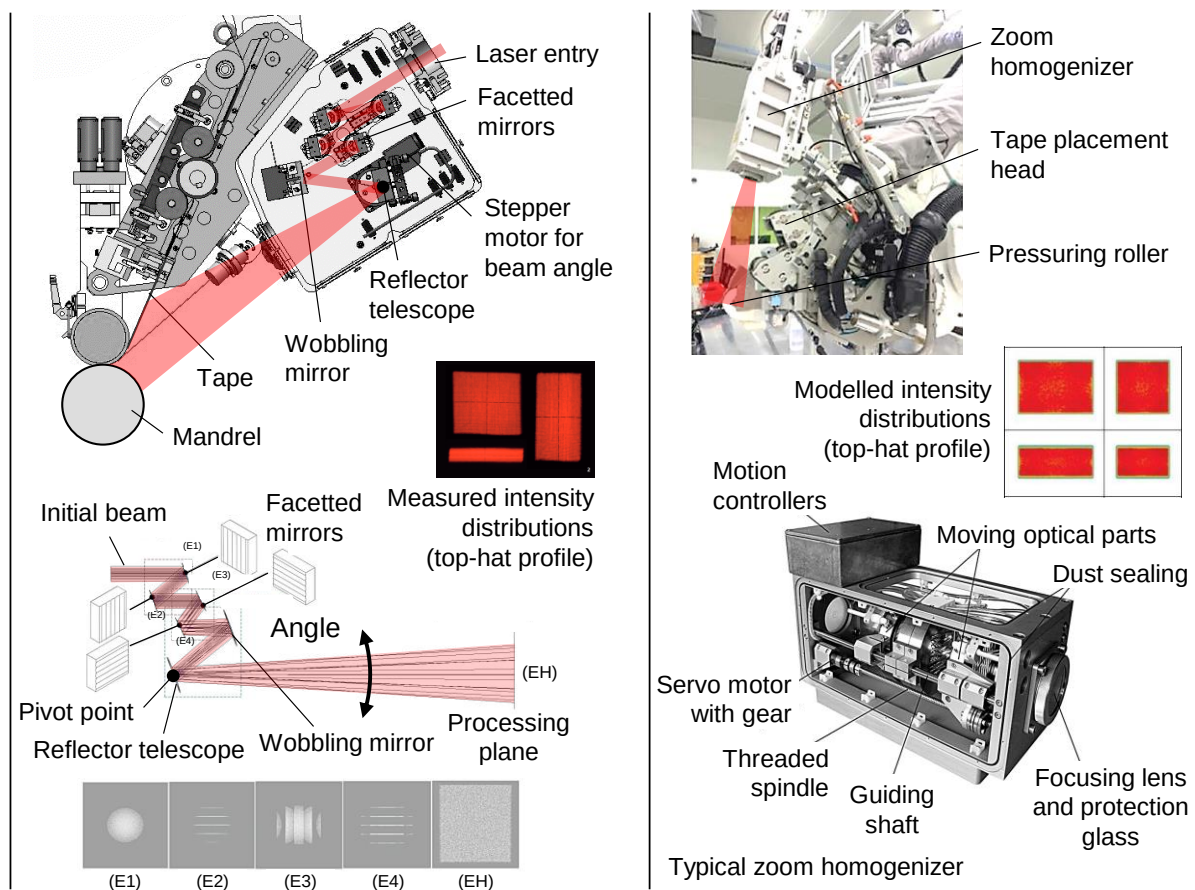


Figure 2.4: Left: Tape placement system with CO₂ laser source, using multiple faceted mirrors for beam shaping and guidance [STIM14, p.86] as well as measured intensity distribution [ILT17]. Right: Fiber-coupled diode laser with motorized zoom homogenizer [SOCC16] [CORO17] and modelled intensity distribution [LASE13b]

Links: Tapelegesystem mit CO₂-Laserquelle und Facettenspiegeln zur Strahlformung und -führung sowie gemessene Intensitätsverteilung; Rechts: Tapelegesystem mit Diodenlaser und elektrisch verstellbarer Zoom-homogenisatoroptik sowie modellierte Intensitätsverteilung

Diode lasers with wavelengths of 800-1000 nm offer the possibility to guide the beam with optical fibers and shape it within encapsulated lenses, instead of sensitive mirrors. These advantages have recently been utilized in tape placement systems by the company Coriolis Composites (Figure 2.4, top right). The system includes a motorized zoom homogenizer by the company Laserline GmbH, which enables the online adjustment of beam width and height by internal positioning of lenses [LASE13].

2.1.3 Individual Tape Irradiation

Individuelle Tapebestrahlung

None of the so far presented systems allow for an adjustable irradiation of *individual* tapes. A novel laser device, recently developed by the Irepa-Laser Institute in cooperation with Airbus and Coriolis Composites, uses multiple collimating optics to illuminate a multitude of 0.25 inch-wide tapes (6.35 mm) individually:

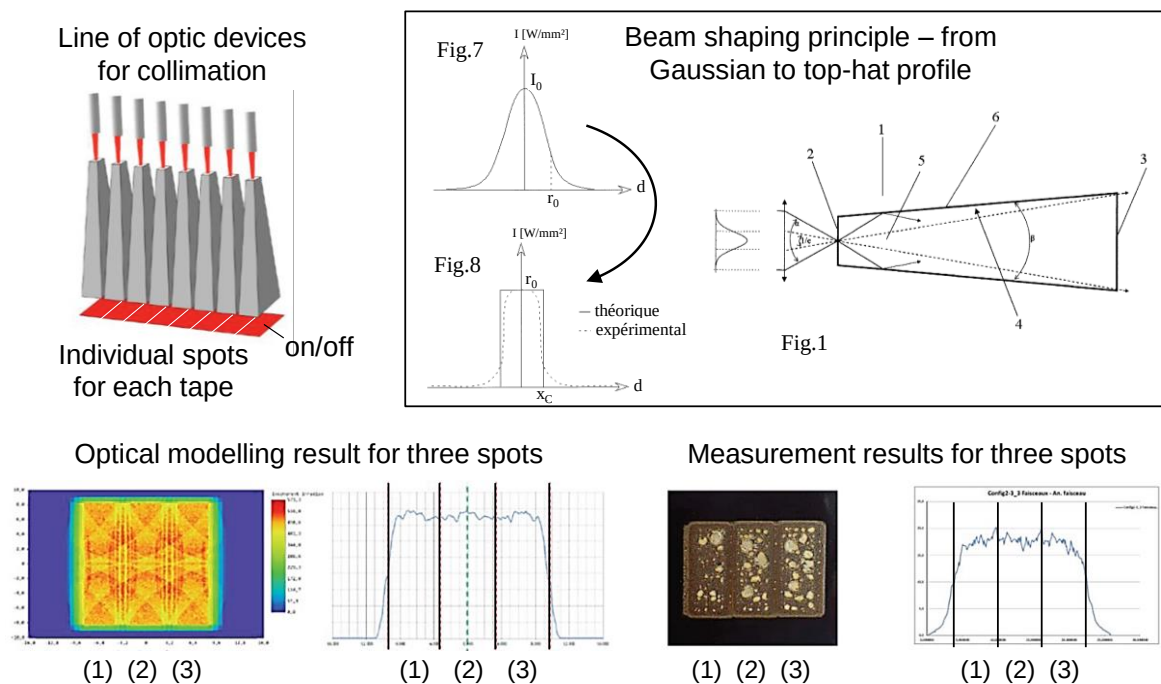


Figure 2.5: Top left: concept for individual tape irradiation; top right: patent drawing of the beam shaping method [US Pat. 8824052]; bottom: optical modelling and measurement of the laser intensity distribution; adapted from [SOCC16]

Oben links: Konzept für individuelle Laserbestrahlung von Tapes; oben rechts: Patentzeichnung des Strahlformungsprinzips; unten: optische Modellierung und Messung der Laserintensitätsverteilung

The beam shaping method utilizes wall reflections within a hollow optical device to transform the (initial) Gaussian beam distribution into a top-hat profile (Figure 2.5, top center). The inner wall of the device is made up of “[...] one or a plurality of facets” to shape the beam accordingly [US Pat. 8824052]. Optical simulations on the homogeneity of the irradiation have been conducted and are reported to correlate with measurements. The laser power is stated to achieve up to 1 kW per tape. Energy losses (from source to workpiece) are reported to be lower than 10%.

2.1.4 Laser Intensity Distributions

Laserintensitätsverteilungen

Until now, none of the presented systems was developed for the *purposeful* use of *laser intensity distributions* (or *irradiance distributions*). In general, laser intensity distributions can be generated by various optical elements, like:

- fixed free-form lenses or faceted mirrors, [KLOC17]
- adjustable lenses or mirrors, e.g. Galvano scanners [KLOC17, p. 4], as well as
- controllable semiconductor lasers, e.g. VCSEL. [DERR15].

Especially the more recently developed semiconductor lasers enable a flexible setting of intensity distributions by the individual energization of chips, lines or stacks. The energization can be controlled in responds times of microseconds [MOEN15, p. 6].

The first proposed use of diode laser *arrays* for tape placement systems can be traced back to 1991 to a lab setup presented by the company Nuvonyx (later purchased by Coherent). The lab setup was soon later scaled to a prototype (Figure 2.6, top left) [AUGU14b]. The system was tested by Boeing (at that time McDonnell Douglas) [HAAK05].

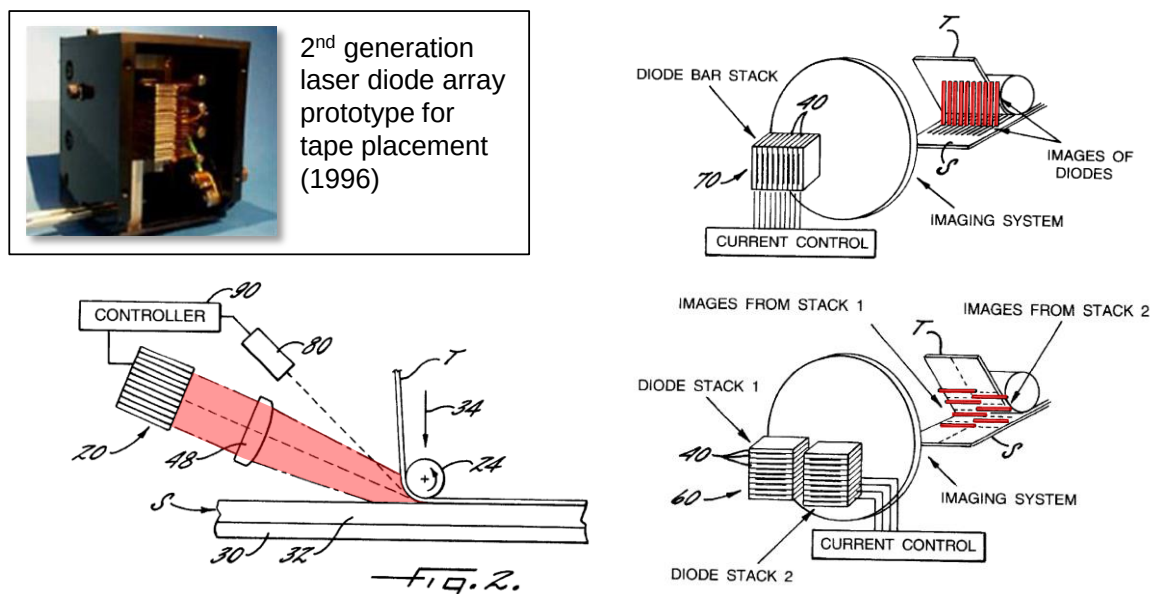


Figure 2.6: Patent drawings of independently controllable laser diode stacks for tape placement; adapted from [HOLM02] and [AUGU14b]

Patentzeichnung individuell ansteuerbarer Diodenstapel für das Tapelegen

A patent drawing (from 2002) by Boeing shows the use of diode stacks in combination with secondary optics for beam focusing (Figure 2.6, “imaging system”) [US Pat. 6451152B1]. Two arrangements were presented: one in which the diodes are stacked in the *width direction* of the process zone (top right) and one in which two diode stacks are placed parallel in the *feed direction* of the tape (bottom right).

In case the diodes are stacked in feed direction, the width flexibility is only enabled by a *discrete* energization of entire stacks (as shown exemplary by two stacks in Figure 2.6, bottom right). The use of additional thermal sensors was proposed to obtain information of the temperature distribution to realize a closed-loop control.

The use of diode laser stacks for the control of *thermal profiles* was presented recently again in an article by GRALD & GOINGS. Here, a diode laser stack was combined with an optical device for collimation; the attributes of the optical device were not presented: The laser was provided by the company Lasertel and was tested by Fives Cincinnati in a tape placement system (Viper 6000 ®) [GRAL16] [LASR17b]:

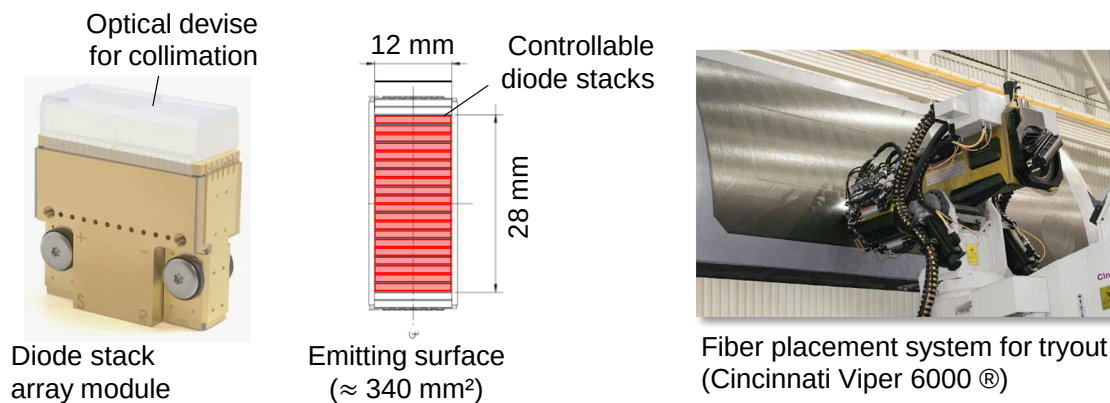


Figure 2.7: Left: diode laser stack with optics for collimation [GRAL16]; middle: emitting surface (near field) [LASR17a]; right: fiber placement system for tryout [FIVE17]

Links: Diodenlaserstapel mit angebundener Optik zur Kollimation; Mitte: emittierende Fläche (im Nahfeld); rechts: Tapelegesystem zur Erprobung

VCSEL. The use of Vertical-Cavity Surface-Emitting Lasers (VCSELs) for thermoplastic tape placement has been introduced by DERRA in cooperation with the Fraunhofer Institute for Production Technology (IPT) and the Aachen Center for integrative Lightweight Production (AZL) in 2015 [DERR15] (Figure 2.9, next page).

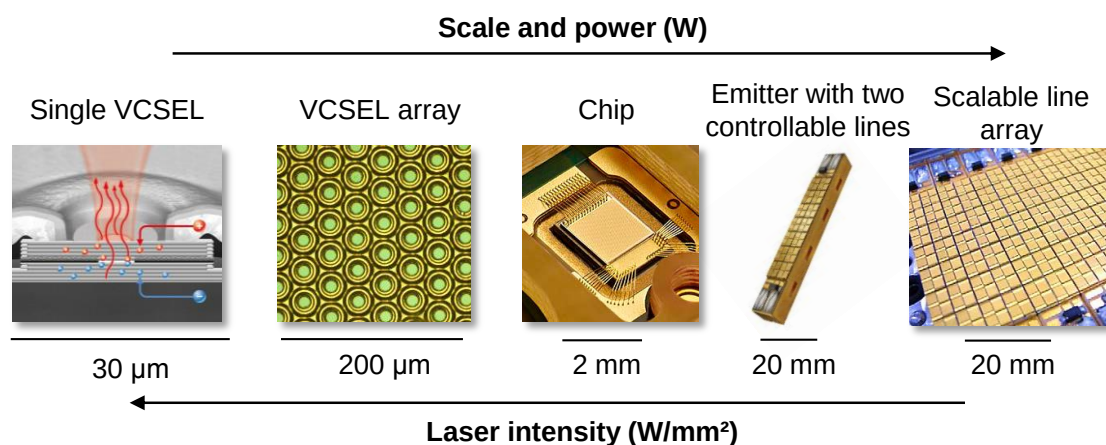


Figure 2.8: Vertical-Cavity Surface-Emitting Laser (VCSEL) technology [MOEN15]

Technologie der Oberflächenemitter

This relatively novel type of laser consists of many thousands of micro lasers, emitting vertically – more precisely perpendicular – to its surface (Figure 2.8).

By packing thousands of micro lasers as densely as possible, high overall laser powers are achieved; available wavelengths are 808 nm and 980 nm. An amount of 2205 single micro lasers are placed on a wire-bonded chip; 56 of these chips are placed in a line of four rows; 28 of these chips are electrically connected in series (Figure 2.8). Such two rows can be controlled electronically by a driver unit (see Figure 2.9, right).

Table 2.1: Attributes of the VCSEL technology [MOEN15]

Eigenschaften der VCSEL-Technik

	VCSEL (micro laser)	Chip	Controllable emitter line	Emitter block: 2 lines/4 rows	Module (line array)
Consisting of:	1	2205 VCSEL (micro lasers)	28 chips	56 chips	placed no. of lines, N
Power	0.0032 W	7.1 W	200 W	400 W	400 W x N
Area [mm²]	$\pi(0.005)^2$	1.8 x 1.7	40 x 4.3	40 x 8.6	40 x 8.6 x N
Maximum intensity	41 W/mm ²	2.3 W/mm ²	1.16 W/mm ²	1.16 W/mm ²	1.16 W/mm ²

Table 2.1 shows the laser intensities at different scales: single VCSEL (micro laser), single chip, emitter line and module (system). Differences between micro lasers and chips emerge because of the area between the single micro lasers (Figure 2.8); differences between the chips and the emitter lines emerge because of the remaining space between the chips. Gaps between the emitters reduce the intensity slightly further. The intrinsic irradiance distribution on the tape/substrate has been modelled in [WEIL16b].

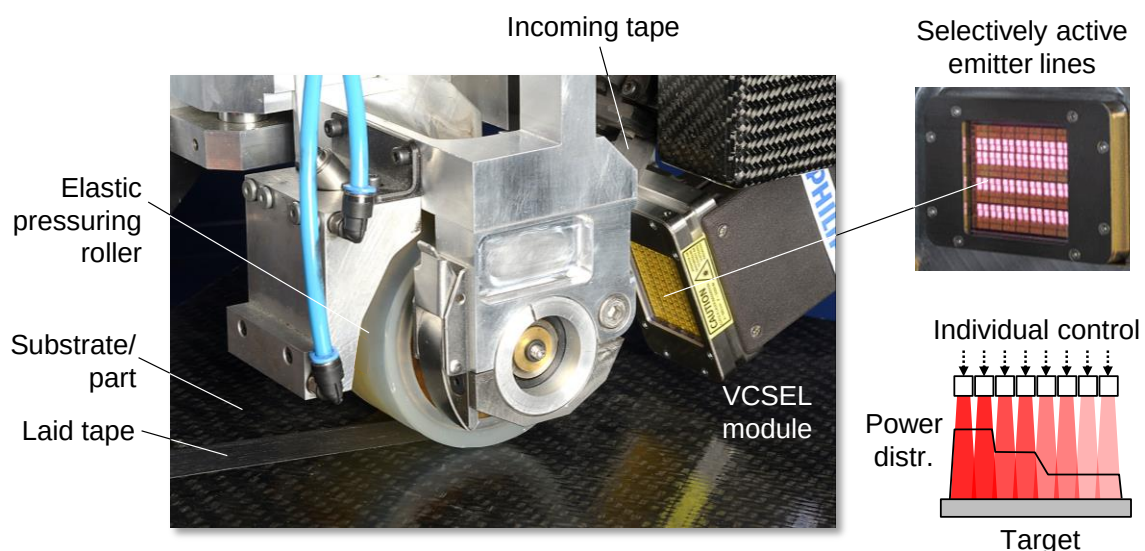


Figure 2.9: Tape placement system equipped with VCSEL technology

Tapelegesystem ausgestattet mit VCSEL-Technik

The *smallest controllable heating width* of a conventional VCSEL module is defined by the width of the emitter lines – roughly 4.3 mm (in the near field). This smallest controllable width increases with higher distance to the emitting surface, due to the *divergence* of each single VCSEL, approximately 20° [MOEN15, p. 2]. The individual control of each emitter line enables an on-off switching in microseconds and a setting of intensity profiles (W/mm²/mm). The number of emitters can be scaled quasi-infinitely wide by packing more emitter lines into a module (Figure 2.8, right-hand side) – assuming the machine design space allows for larger cooling peripherals.

Integrated Modules. The emitters are integrated in rather compact modules, containing cooling peripherals, power supply peripherals and a mechanical housing. One module was available during the course of this thesis (Figure 17.1, p. 185, bottom right). Such a module can be positioned in the infeed area of a tape placement system (Figure 2.9).

Module Positioning. Additional mechanical systems can be used to assist in the positioning of the modules. A *positioning holder*, developed for this theses, is documented in the Appendix in Figure 17.2.

2.1.5 Interim Conclusion

Zwischenfazit

The state-of-the-art research showed that tape placement systems with adjustable laser irradiation can be distinguished by three characteristic features:

- By the means of adjustment: *manual* (human technician), or *automatic ones* (electromechanical or direct electronic control)
- by the possibility for adjustment *during* the process or with the prerequisite of a *turned off* machine (online/offline) and
- by the required amount of *moving masses*, which (in general) increase the response time of the temperature control (Figure 2.10, next page).

From these features, nine possible *methods* for adjustable irradiation can be defined and are shown in Figure 2.10 with the assigned numbers (1) to (9). These methods will later be ascribed to the identified systems from the literature (Table 2.2).

To get an impression on the differences in moving masses, the figure shows the exemplary case of a diode laser system (right-hand side): KOELZER used the automatic tilting of the whole laser system – method (5) – including energy supply, laser source and beam shaping optics. The overall weight was 28 kg [KOEL08, p. 31]. The system was *not* fiber-coupled. A fiber-coupled diode laser of the company Laserline weights roughly 50 kg [LASE13a]. However, in this case, the laser source and energy supply can be placed externally from the placement head, while only the optic is positioned for laser beam control. BRECHER et al., STEYER, KERMER-MEYER and the company AFPT GmbH utilized this possibility for automatic laser angle adjustment in [BREC14a] [AFPT17a]. The moving masses are below 5 kg. In case electromechanical zoom

homogenizers are used, the moving masses are below 1 kg. Using direct laser technology, like VCSEL, avoids mass positioning at all, leading to minimized response times. More precise temperature controls are the expected consequence.

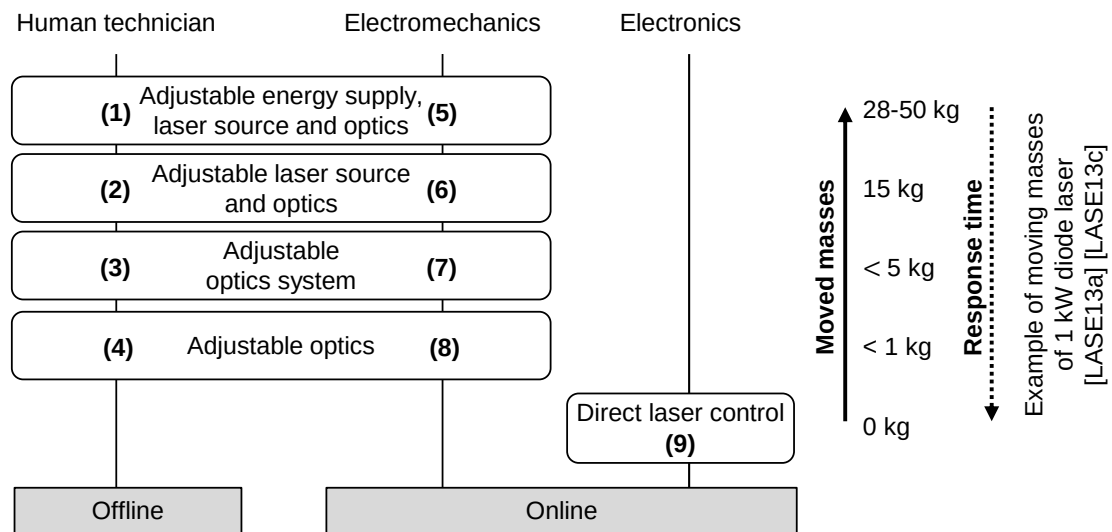


Figure 2.10: Classification of methods for adjustable irradiation in tape placement systems
Klassifizierung von Methoden einstellbarer Bestrahlung in Tapelegesystemen

It can also be reported that the proposed systems with direct lasers require closer positioning to the process zone, due to the inherent laser *divergence* angle (roughly 20° for VCSEL). Close positioning of the laser next to the nip point reduces the accessibility for optical sensors, like pyrometers, and can expose the laser to the risk of contamination. Additional optical elements for micro collimation could improve this situation and further propel the use of semiconductor lasers in tape placement systems (Figure 2.9 and Figure 2.5). The collimation method, shown in the patent drawing in Figure 2.5, is expected to be rather difficult to realize, due to inherent divergence of diode lasers at the micro level. Its implementation has not been reported so far.

The further use of the prototype in Figure 2.6 (p. 20) is also not known. Still, several recent developments show that flexible irradiation by semiconductor lasers offers clear advantages and novel possibilities for thermal control – the next section will present several examples of this.

Irradiation Attributes. Summarizing, state-of-the-art tape placement systems are able to provide five basic irradiation attributes so far:

- (1) laser beam angle positioning,
- (2) spot width and (3) spot height as well as
- adjustment of the intensity distribution in either (4) feed or (5) width direction.

The subsequent table summarizes the findings. Additional sources are added. The systems are classified by their ability to change the irradiation attributes during the process (online) or not (offline).

Table 2.2: Categorization of laser-assisted tape placement systems from the state of art
Kategorisierung lasergestützter Tapelegesysteme des Stands der Technik

Ref.	Laser source	Optics	Adjustable irradiation attributes						Method (p. 24)
			Laser angle	Spot		Intensity distribution			
				Width	Height	Number of spots	in width	in feed	
[SCHM94]	Nd:YAG	Focusing optic (ellipse)	Offline	Offline	Offline	N/A	N/A	N/A	(3)
[ESCH01]	Nd:YAG	Scanner	Offline	Offline	N/A	N/A	N/A	N/A	(7),(8)
	Diode laser	Homogenizer optic	Offline	Offline	N/A	N/A	N/A	N/A	(7)
[HOLM02]	Direct edge emitter	Focusing optic	N/A	Online	Online	Online	Online	Online	(9)
[KOEL08]	Diode laser	Direct homogenizer	Online	N/A	N/A	N/A	N/A	N/A	(6)
[STEY13]	Diode laser	Fiber-coupled homogenizer	Online	N/A	N/A	N/A	N/A	N/A	(7)
[BREC14a]	Diode laser	Fiber-coupled homogenizer	Online	N/A	N/A	N/A	N/A	N/A	(7)
[STIM14]	CO ₂ laser	Facetted mirrors	Online	Online	Online	N/A	N/A	N/A	(8)
[HENN14]	Diode laser	Fiber-coupled homogenizer	Online	N/A	N/A	N/A	N/A	N/A	(7)
[SOCC16]	Diode laser	Motorized zoom optics	Online	Online	Online	N/A	N/A	N/A	(7),(8)
[AUGU15]	Nd:YAG	Fiber-coupled homogenizer	Offline	N/A	N/A	N/A	N/A	N/A	(3)
[DERR15]	VCSEL	-	N/A	Online (either or)		Online	Online	Online	(9)
[SOCC16]	Unknown	Collimation optics	Unkn.	Online	N/A	Online	N/A	N/A	(9)
[WEIL16b]	VCSEL	-	Offline	Online (either or)		Online	Online	Online	(9),(3)
[GRAL16]	Direct edge emitter	Collimation optics	Unkn.	Online	N/A	N/A	Online	Online	(9)

It can be observed that several of the presented systems enable a change of the laser beam angle. Systems that enable controlled intensity distributions in *both directions* of *feed* and *width* have been proposed – Figure 2.6 –, but not realized yet. In general, a clear trend towards more flexible and online-adaptable irradiation can be observed, however, further advances are required to utilize all benefits of customized irradiation. It is assumed that previous developments were either *pushed* by novel laser system technologies, or *pulled* from process engineering, due to discoveries of novel process requirements or potentials for process improvements. The demand (“*pull*”) for adjustable irradiation will be the topic of the next section.

2.2 Application and Benefits of Adjustable Laser Irradiation

Anwendung und Nutzen einstellbarer Laserbestrahlung

In the last three decades, the irradiation flexibility in laser-assisted tape placement systems increased continuously. As will be shown, the reasons for this were as diverse as the systems themselves. Several authors investigated the use of adjustable irradiation solely by process *simulation* and *theorizing*. Consequently, not all of the research work has been transferred into tape placement systems. The analysis of the literature showed four domains of *purposes* thus far:

- 1) Avoidance of unnecessary heating,
- 2) Response to changing thermal conditions,
- 3) Response to changing optical conditions and
- 4) Specific setting of thermal conditions within the material.

The following subsections will present the state of the art on each domain.

2.2.1 Avoidance of Unnecessary Heating

Vermeidung unnötiger Erwärmung

Like most manufacturing systems, tape placement machines must be able to process a variety of pre-products, to achieve flexibility in production. The pre-product (tape) can vary in its material *composition* – fiber and matrice – as well as in its *geometrical attributes* – thickness and width (Figure 1.1, p. 4, Figure 18.1, p. 187, Figure 18.2).

In most of today's (thermoplastic) tape placement systems, one single laser spot has been implemented to enable the processing of different widths [SCHM94] [ESCH01] [KOEL08] [STEY13] [AUGU15] [KERM15] (Figure 2.1 to Figure 2.4) or a multitude of tapes [KOEL11] [DUBR15]. Unintentional irradiation left and right from the tape(s) can lead to several drawbacks and practical issues:

Firstly, the energy efficiency of the placement process is reduced, because the laser power is not fully utilized for the welding zone, instead leading to unnecessary heating of the surroundings (roller, previous layers and guide channels). This also reduces the maximum achievable surface temperature (at high speeds), which could otherwise be realized with the power of the available laser source.

Secondly, the roller heats up unnecessarily, due to irradiation left and right from the tape. Internal and external cooling of the roller can help to reduce its heating [HENNE14, p. 5], but not fully avoid it: The use of translucent silicones has been introduced to reduce absorption in the roller [STEY13, p. 68-71]. However, contamination of the initially translucent roller leads to absorption at its surface. Already a single overheating of the tape can lead to this effect. If the roller is not cleaned, the initial minor contamination can initiate a self-enhancing cycle of steadily increasing surface absorption and overheating. Elastomers or silicones lose their durability at elevated temperatures (by embrittlement) [MARS04, p. 402] [SCHO13, p. 40].

This is especially problematic at high thermal loads, which generally occur during processing of high-temperature polymers, like PEEK or PPS ($> 300^{\circ}\text{C}$). Renewing the roller costs valuable machine time and reduces the overall equipment effectiveness.

Thirdly, alternating mechanical loads at elevated temperatures can lead to the hardening of elastic roller materials [PAES16] [MALE16, p. 7]. The roller can therefore lose its ability to conform to the curvatures of the substrate. This can affect the pressure length and distribution on the tape during consolidation.

Finally, in case only one narrow roller is used, irradiation left and right from the roller leads to unwanted heating of machine parts [GRAL16, p. 3], machine surroundings or previously laid layers [SOCC16, p. 132]. This can be especially problematic when unfocused heating systems are used, like infrared heaters. Guiding channels for the tape, close to the nip point, generally increase the positioning accuracy during the adding process (Figure 2.11), but can commonly not be used in thermoplastic tape placement systems, because of overheating issues [AUGU14b, p. 8].

The stated disadvantages of single wide irradiation spots come together in the case of parallel near-net shaping where a multitude of tapes have to be heated and applied simultaneously (Figure 2.11). Cut and add steps lead to a continuously changing application width, making the irradiation of roller and machine elements inevitable:

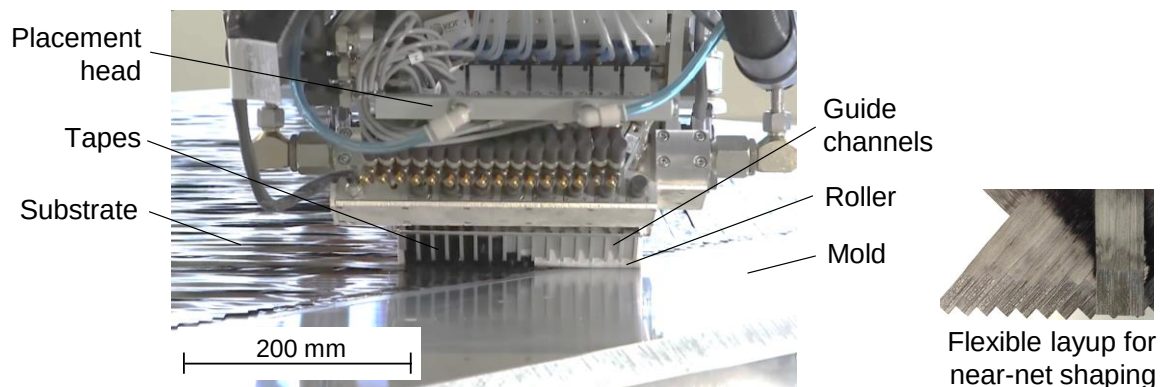


Figure 2.11: Continuously changing application width during multi-tape application of 12 mm-wide tapes for near-net shaping (in this case thermoset preregs) [COMP17]; potential application for *individual* irradiation of thermoplastic tapes *Stetig wechselnde Applikationsbreite bei der endkonturnahen Mehrfach-Ablage von 12 mm breiten Bändern (in diesem Fall Duroplast-Preregs); potentielle Anwendung für die individuelle Bestrahlung von Thermoplast-Tapes*

The presented system in Figure 2.5 (p. 19) may be a suitable laser technology to solve this issue. To the knowledge of the author, this kind of placement system has not been realized so far; however, its implementation seems to be the logical next step.

In conclusion, increased irradiation flexibility can enable the targeted irradiation of changing tape widths and changing number of tapes during adding and cutting. Unwanted heating of the roller and the peripherals should be prevented or minimized. Flexible irradiation widths are one of the most often mentioned reasons for the presented systems in the previous section (Figure 2.1 and Figure 2.4 to Figure 2.7).

2.2.2 Responds to Changing Thermal Conditions

Reaktion auf wechselnde thermische Zustände

Thermoplastic tape placement is an additive manufacturing process. Controlling the surface temperature throughout the whole manufacturing cycle, of tape *and* substrate, is of utmost importance to reach reliable mechanical properties of the final part. To achieve this condition, many developed tape placement systems include a laser-power-based temperature control and the possibility of *dissimilar irradiation* of *tape* and *substrate* (Figure 2.1, Figure 2.4). The reasons for dissimilar irradiation are manifold:

Firstly, a thick non-preheated substrate can act as strong heat sink [GROU12, p. 29]. In this case, the substrate requires stronger heat input than the tape, to reach a desired surface temperature for consolidation. Vice versa, the substrate can approach the welding zone already preheated, due to a heated mold or a preceding placement process. In such a situation, the control requirement is reversed: the substrate needs less heat input, because overheating of the polymer has to be avoided. [STEY13, p. 57] A typical example for this phenomenon is the manufacturing of rings of small diameters. Here, the interval of repetitive heating is very short, leading to heat accumulation within the ring, so that the laser power has to be reduced accordingly.

Secondly, the transfer of heat from the surface inwards depends on the thermal diffusivity α of the material, which is a function of its heat capacity c_p , density ρ and thermal conductivity k_z in the thickness direction z :

$$\alpha = \frac{k_z}{\rho \cdot c_p} \quad (2.1)$$

The thermal diffusivity α generally changes when the tape material is changed, e.g. from carbon fiber to glass fiber. It can also change in transition areas, e.g. from a pure plastic liner to an already reinforced area of the part, during overwrapping (e.g. in Type 4 pressure vessels or bonded composite pipes [COVE17] [CFT17] [AIRB17]).

Thirdly, the heat transfer can be influenced by the body thickness d . With more deposited layers, the overall thickness grows, leading to the possibility of higher heat penetration. [GROV88, p. 369]

In order to achieve reliable weld strengths throughout the manufacturing process, the tape placement system has to *respond* to the mentioned changing thermal aspects. The physical principles will be important throughout this thesis. Therefore, the basics will be introduced here: In general, both surface heat flux $\dot{q}_0$ and irradiation time t_L affect the transient heat transfer in a body and thereby its surface temperature:

$$T_{surface} = f(\dot{q}_0, t_L, \text{body attributes}) \quad (2.2)$$

The specifics of this correlation will be discussed later in much more detail. For now, it is important to notice that the surface temperature $T_{surface}$ can be controlled by the laser power P_L , because the laser power is proportional to the surface heat flux $\dot{q}_0$ (assuming optical phenomena to be constant):

$$\dot{q}_0 \sim \frac{P_L}{A_L}; \quad A_L = x_L \cdot w_L; \quad w_L \approx w_{tape} \quad (2.3)$$

with A_L being the irradiated area of the laser beam, which corresponds to the irradiated length x_L multiplied (approximately) by the tape width w_{tape} . From Equation 2.2 it follows that the surface temperature $T_{surface}$ can also be controlled via the process speed v_p and the irradiation length x_L , because for the irradiation time t_L applies:

$$t_L = \frac{x_L}{v_p}, \quad (2.4)$$

This is why it becomes increasingly difficult to reach a target surface temperature at higher speeds. Changing the laser angle α_L changes the irradiated lengths x_L on the tape and substrate respectively (compare Figure 2.2 or Figure 9.2, p. 141):

$$x_L = f(\alpha_L) \quad (2.5)$$

Therefore, the laser angle α_L can be used as an additional control variable to achieve individual control of the tape/substrate surface temperature [STEY13, p. 49]. The exact correlation between α_L and x_L depends to the specific design of the system, e.g. by the position of the laser angle pivot point (Figure 2.1 and Figure 2.4).

Finally, several authors realized that the exact correlation between surface heat flux $\dot{q}_0$ and $T_{surface}$ depends on the surface heat flux *distribution* $\dot{q}_0(x)$ [GROU12, p. 9-32]. $\dot{q}_0(x)$ can be utilized to change the transient heat transfer process [STOK16b, p. 194].

In conclusion, various thermal conditions can change inevitably during a manufacturing cycle. The energy input in the tape and substrate can be controlled independently by the laser angle α_L , laser power P_L and heat flux *distribution* $\dot{q}_0(x)$.

2.2.3 Responds to Changing Optical Conditions

Reaktion auf wechselnde optische Zustände

Not only thermal conditions can change during a manufacturing cycle, but also *optical* ones: such a change is illustrated in the US Patent 6451152B1 (Figure 2.12, next page). Here, adjustable intensity is proposed to respond to geometrical changes along the placement path. Those changes can lead to increased (or decreased) intensity (“illumination”), depending on the direction of geometrical change. Without such an adaptation, unwanted fluctuations of the surface temperature are the stated result.

This issue was confirmed in process trials for 2.5-dimensional parts at the Technical University Munich and are presented in [KOLL16, p. 5] (Figure 2.13). Two reasons for the fluctuating surface temperature were mentioned: (1) the machine/laser standstill, due to limited robot dynamics, and (2) increased absorption, due to lower incidence angles. A third reason was described in [WEIL16a, p. 3-4]: (3) increased local heat flux (W/mm²) during the transition phase from flat to curved surface geometries. The maximum increased local heat flux was found to be 200%. Interestingly, this issue cannot be solved by adapting the laying speed v_p or laser power P_L .

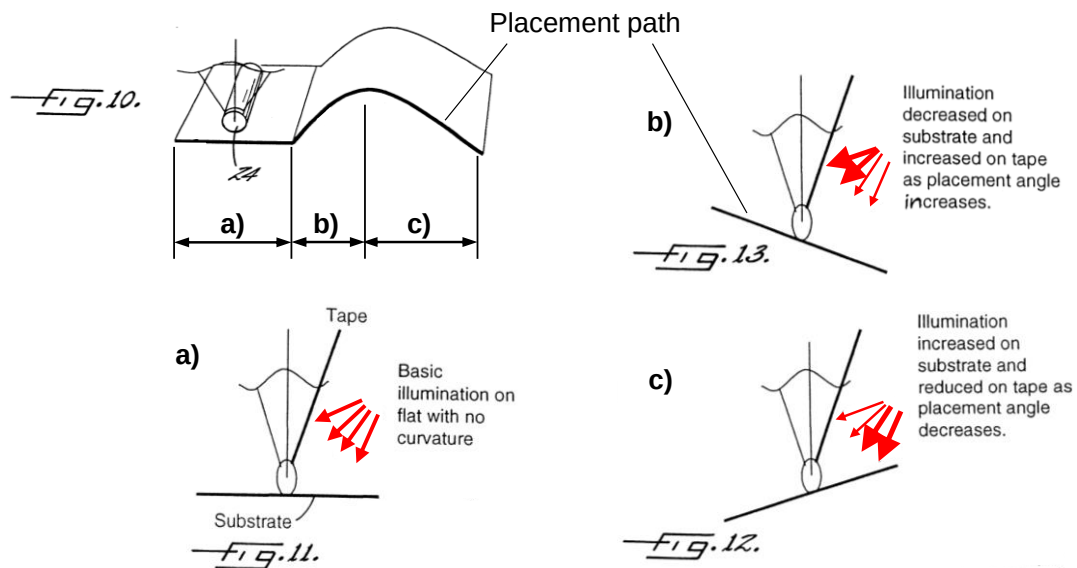


Figure 2.12: Proposed use of adjustable irradiation in the feed direction to compensate changing irradiation conditions on the substrate; adapted from [HOLM02, p. 4]
Vorgeschlagene Nutzung von flexibler Bestrahlung in Vorschubrichtung zur Kompensation wechselnder Bestrahlungsbedingungen

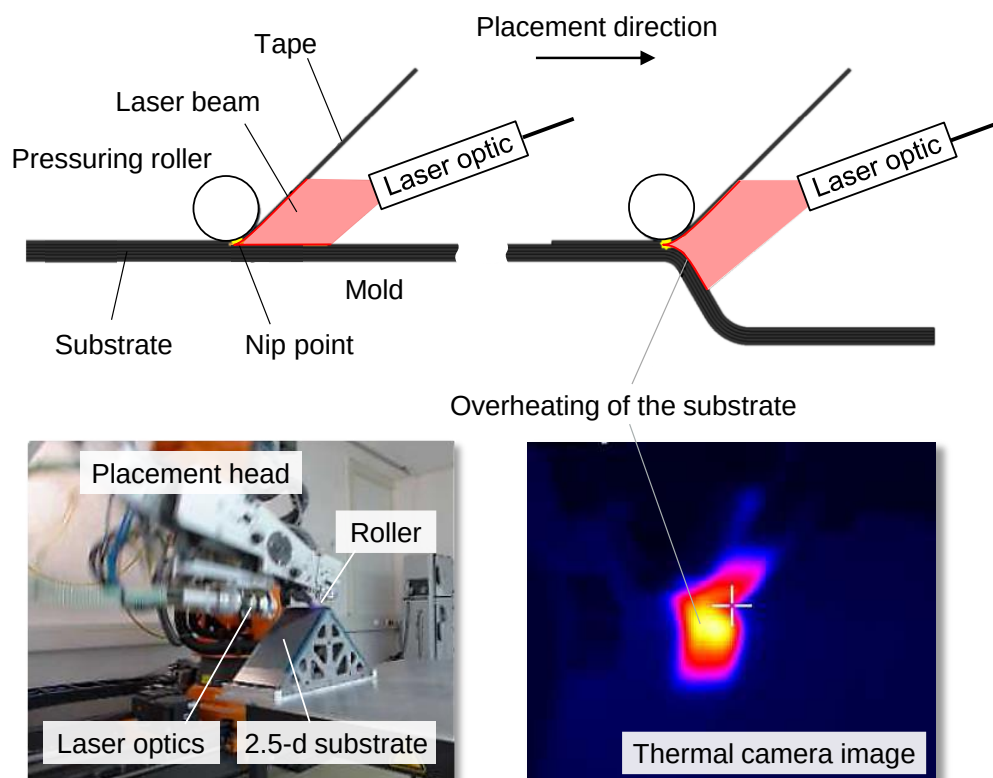


Figure 2.13: Investigations of KOLLMANNSEBERGER et al. on the surface temperature development at the transition point from flat to curved geometries; adapted from [KOLL16, p. 3, 6].

Untersuchungen zur Entwicklung der Oberflächentemperatur an Übergangsstellen von flachen zu gekrümmten Oberflächen

2.2.4 Targeted Setting of Thermal Material Conditions

Gezielte Einstellung thermischer Materialzustände

Thermal Condition in Material *Width* Direction

The presented patent in the previous section states also the possibility of purposeful non-homogeneous heating along the material width. By this, the material flow can be controlled according to the placement path during steering (Figure 2.14). It is stated that conventional (homogeneous) heating methods demand a slowdown of the placement head before steering, to avoid “[...] *puckering or wrinkling*” [HOLM02, p. 1].

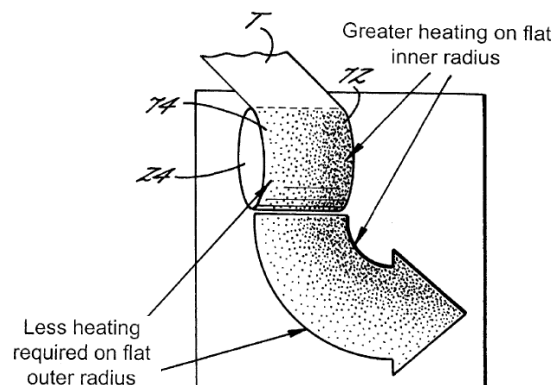


Figure 2.14: Process control concept for higher placement speeds during tape steering by customized laser intensity according to the laying radius [HOLM02, p. 5]

Prozesssteuerungskonzept für höhere Ablegeraten während Bahnkurven durch zugeschnittene Laserintensität in Abhängigkeit vom Ablegeradius

To reduce these effects at high placement speeds, it is stated that the material should be heated according to the laying radius. The feasibility of this control concept remains to be proven. Since 2002, no literature source is known to the author.

Thermal Conditions in Material *Feed* and Material *Thickness* Direction

Tape-to-Substrate Temperature Ratio. For in-situ tape placement, the predominant opinion in the literature is that tape and substrate have to be heated in such a way that both end up at *near-equal* temperatures at the nip point. However, thus far it is not yet proven whether this is true regarding the overall objectives of productivity and quality. GROUVE questioned the presumption and suggested to use the available laser power fully for the heating of the tape, rather than for tape and substrate [GROU12, p. 132]. The purpose of this strategy is to use the heat accumulation in thin tapes and avoid internal heat losses in the (mostly) thicker substrates. In such a scenario, the tape is supposed to act as the “heat source” for the development of intimate surface contact and autohesion. For this strategy it is advantageous that thermal-resistant matrices, like PEEK, can be heated high above the melting temperature without degrading. Unfortunately, no experiments on this strategy have been presented so far. A reversed strategy – complete melting of the substrate $> 2 \times T_{melting}$ and feeding of a cold tape – might also be a feasible alternative.

Influencing the Heat Soak via the *Irradiation Length*. This subsection approaches the core topic of the thesis. Some authors have hypothesized about the potential benefit of longer heating lengths, e.g. [MOD13, p. 6]. The benefit is supposed to arise from higher thermal penetration of the material (heat soak), which should be beneficial for the bonding process. Because the topic is central to this thesis, the few insightful passages of previous writings are subsequently recited:

Regarding the use of preheaters, AGARWAL et al. stated in 1992 the following: “[In case a preheater is used, the] *material remains at an elevated temperature for a longer period of time, than when a narrow laser beam is used. Heating a large area of material [...] produces smaller cooling rates [...]. The slower cooling rates produce longer melt or dwell times which may have consequences in the consolidation quality of the part*” [AGAR92, p. 121, 124]. No quantitative investigations were presented by the authors.

Five year later, SONMEZ & HAHN point out that “*The effect of larger heated lengths is similar to the effect of preheating the substrate in slowing down the cooling rate and thus increasing the residence time in the melt. [...] Using a large heated length is then more favorable to consolidation quality*” [SONM97a, p. 217-219]. However, again, no experimental proof of the assumption was demonstrated. Recently (2015), STOKES-GRIFFIN & COMPSTON recognized again that “[not only does] *the heat source need to supply enough heat to the surface of the composite to achieve a sufficient consolidation temperature, it also must provide enough heat soak to prevent excessive cooling rates/maximise dwell time*” [STOK15a, p. 279]. While discussing optimal heating profiles, the authors wrote: “*One method to increase the heat soak is to lengthen the heating zone [...]. Higher temperatures can be used [for higher heat soak], however, thermal degradation must be avoided*” [STOK16b, p. 192]. This realization led the authors to discuss the use of purposely intensity distributions (next subsection).

These statements lie 24 year apart, yet all point in the same direction: The thermal penetration is *somehow* relevant for the bonding process and can be influenced by the heating (or irradiation) length. The findings were derived from analysis of a limited number of singular numerical simulations. Models that correlate the heated length to the heat soak and then to the weld strength have not been presented yet.

Influencing the Heat Soak via the *Surface Heat Flux Distribution*. Surprisingly little is known about the “ideal irradiation” in tape placement. STOKES-GRIFFIN & COMPSTON were the first authors to question the (conventionally occurring) surface heating profile. In normal operation setups, the surface temperature development $T_{surface}(x)$ is an inherent consequence, caused by several factors, like laser power P_L , thermal diffusivity α , material thickness d_{tape} and surface heat flux distribution $\dot{q}_0(x)$, which again is caused by optical conditions of the laser system setup (e.g. roller diameter, laser angle, top-hat laser spot profile, reflection). Instead of taking the occurring heating profile for granted, the authors tested various (hypothetical) heating profiles on three attributes: (1) maximum heat soak (for high weld strength), (2) mitigation of potential degradation, (3) minimum required power.

To generate the (hypothetical) surface heating profiles $T_{surface}(x)$, an *inverse* numerical model was used to determine the required surface heat flux distribution $\dot{q}_0(x)$. The results are revised in Figure 2.15 (surface heating profiles at the top; respective heat flux distributions at the bottom). Unfortunately, the heat soak in the through-thickness direction z cannot be derived from the graphs.

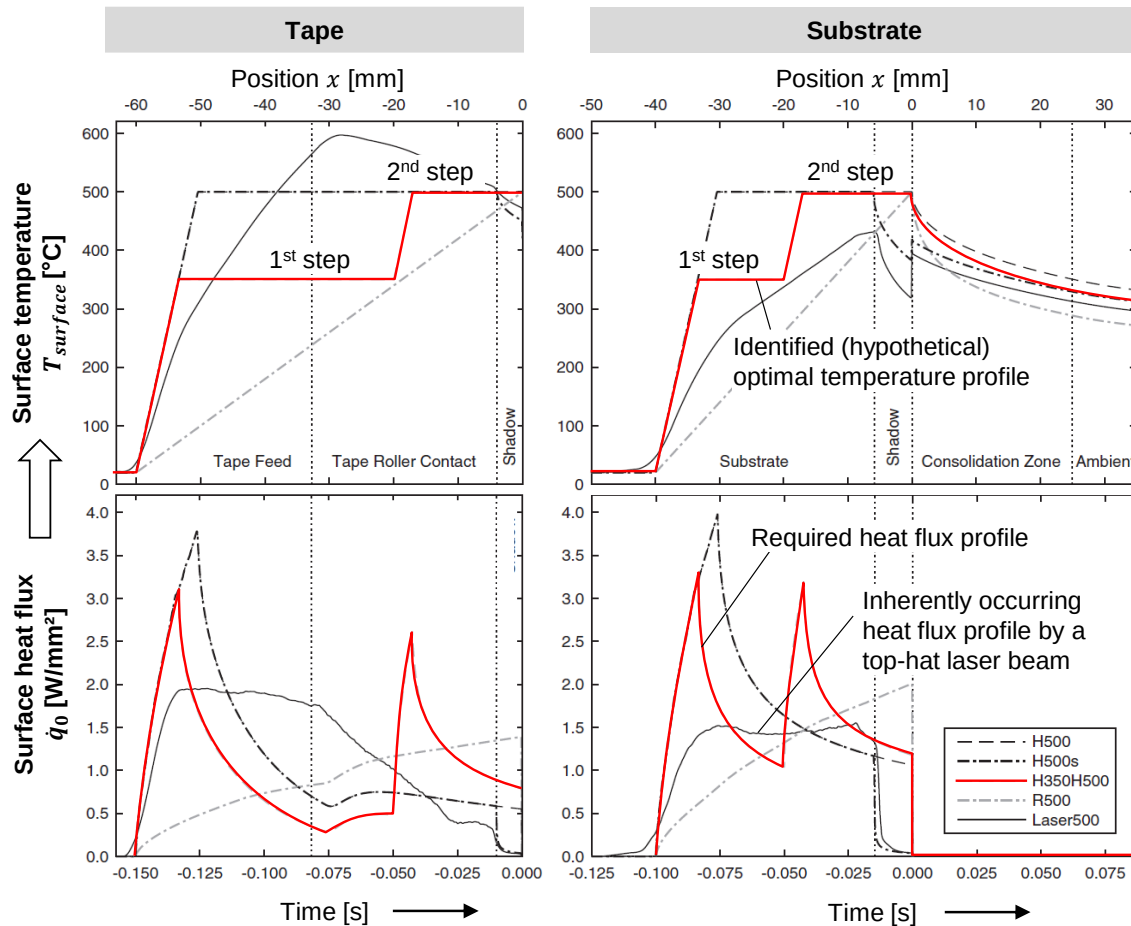


Figure 2.15: Hypothetical surface heating profiles with required surface heat flux distributions for tape (left) and substrate (right); adapted from STOKES-GRIFFIN & COMPSTON [STOK16b, p. 194]

Hypothetische Erwärmungsprofile der Oberfläche mit erforderlicher Wärmestromdichte an der Oberfläche für Tape (links) und Substrate (rechts)

It was found that a two-step heating profile achieves the highest benefits (thermal profile $H350H500$, marked in red). During a first heating step, a surface temperature of 350°C is established quickly by a strong decaying surface heat flux $\dot{q}_0(x)$. The surface temperature is kept constant, slightly above the melting temperature for a certain period of time, by decreasing the heat flux accordingly. During this period, maximum heat soak is established, without overheating the polymer at the surface. In a second heating step, the surface temperature is elevated to 500°C.

The strategy was found to achieve highest (theoretical) bonding strength, due to a high heat soak with additional benefits of less needed power compared to the profile $H500$ and a lower risk of thermal degradation. Experimental validation of the thermal profiles and the predicted bonding strengths have not been presented yet.

2.2.5 Interim Conclusion

Zwischenfazit

The subsequent table summarizes the previous findings. Further findings from the thermoplastic tape placement literature are added.

Table 2.3: Summary of applications and benefits of adjustable laser irradiation

Zusammenfassung der Anwendungen und Vorteile anpassbarer Bestrahlung

Adjusted irradiation parameter		Stated application and processing benefit	Ref.
Laser angle		Major reason: Dissimilar heat input in tape and substrate	
		Lower required heat input in case of heat accumulation in substrate, e.g. in rings, to avoid overheating	[SCHM94]
		Adaptive heat input in case of preheated substrates (by a heated mold or preceding placement process)	[SCHM94]
		Response to dissimilar absorptance of the tape and substrate surface	[SCHM94]
		Reinforcing of non-reinforced thermoplastics, like liners for pressure vessels (different thermal/optical properties)	[KOEL08]
		Controlled tape-to-substrate surface temperature ratio	[GROU12]
		Influencing the reflectance, by changing the incidence angle	[AUGU14b]
Spot	Width	Major reason: Adjusting to the application width	
		Avoidance of overheating or reheating of laid tapes	[SOCC16]
		Maximization of energy efficiency	[SOCC16]
		Avoidance of unwanted heating of the surroundings	[GRAL16]
	Height	Major reason: Adjusting the heating length	
		Adjusting the heating length to the tape feed rate, in order to keep the surface temperature constant	[HOLM02]
		Influencing the cooling rate and melt dwell time and the by higher thermal penetration (heat soak)	[AGAR92] [SONM97a]
	Number of spots	Individual heating of tapes to reduce unnecessary heating of roller and surroundings	[SOCC16] [HOLM02] [DERR15]
Intensity distribution	in width	Major reason: Setting of thermal conditions	
		Controlled material flow in tape steering	[HOLM02]
		Compensation of non-homogeneous reflection, e.g. at high winding angles (e.g. 45°) and small diameters	[WEIL16a]
		Compensation of locally differing heat losses	[HOLM02]
	in feed	Major reason: Setting of thermal conditions	
		Compensation of varying incidence angles and varying head speeds in case of changing substrate geometries	[HOLM02]
		Maximization of heat soak for increased bond strength and crystallization, while minimizing the period at high temperature, to mitigate potential thermal degradation	[STOK16b]
		Compensation of the inherent non-homogeneous intensity distribution in the infeed zone at start and stop processes	[WEIL16a]
		Compensation of local heat losses	[HOLM02]

In general, it can be observed that with novel laser technologies for adjustable irradiation, more strategies for process optimizations emerged (Section 2.1). Especially the advent of semiconductor lasers offers new potentials for better thermal control, by the possibility of real-time switching of intensity profiles. Many ideas have been proposed. However, few works are known that tested these new possibilities. Theory and ideas seem to be in advance of the application, not at least because only few tape placement systems enable flexible irradiation so far.

The most neglected field of research can be attributed to the use of intensity profiles for controlled heat soaks. This interesting field has only been investigated theoretically. Practical investigations are not known and testing methods are missing. Finally, there is a lack of understanding on the exact correlation between heating length, heat soak and weld strength.

2.3 Temperature Measurement for Closed-Loop Controls

Temperaturmessung für geschlossene Regelkreise

The previous sections presented the state of development of adjustable irradiation and its use for the placement process. This section will take a step back and present how the thermal process is controlled in practice. State-of-the-art control values will be introduced as well as measurement technologies to obtain these values.

Thermal control is a core competence in in-situ tape placement. Almost all literature sources state that the *surface temperature before bonding* is the most critical value to be controlled for a reliable consolidation quality [SCHM94, p. 68] [ESCH01, p. 31] [KOEL08, p. 2] [STEY13, p. 32, 47] [STIM14, p. 15]; for obvious reasons: The surface temperature indicates the surface's aggregate phase (molten or solid). If the surfaces of tape and substrate reach the melting temperature of the polymer before pressuring, a crucial condition is established to complete intimate surface contact and autohesion (Subsections 6.1.2 to 6.1.4). In case the temperature is too low, the polymer cannot flow and interdiffusion of polymer chains is retarded; is the temperature too high, the polymer is at risk of thermal decomposition. Many experiments have shown this most obvious correlation between surface temperature and weld strength [AGAR96] [STEI96, p. 113] [KOEL08, 122-125] [GROU12, p. 90, 148] [STOK15a].

Contact-Free Sensors. To detect the surface temperature, contact-free radiation thermometers are used, like pyrometers or infrared cameras. The advantages of these sensors are the high measuring frequency and avoidance of mechanical interference with the tape or workpiece. Without exception, all suppliers of tape placement systems utilize this ability to obtain the surface temperature and to realize closed-loop temperature controls (Figure 2.2, 2.3 and 2.16, next page) [BREC16] [AUGU15].

Control and Monitoring. In combination with the low response time of lasers, a near-constant surface temperature can be realized throughout the entire production process [BREC14a]. The surface temperature can also be monitored in order to detect unacceptable temperature deviations, to stop the process, if required.

Sensor Development. Extensive measures have been taken to obtain the surface temperature accurately. The most commonly used sensor is the pyrometer. The device obtains the surface temperature at relatively high measuring frequencies (> 100 Hz), however, spatial information of the temperature *distribution* is concealed. Therefore, KOELZER introduced multi-point radiometers, with a resolution of 16×16 pixel. The sensor was able to measure temperatures along the width of both tape and substrate, however with relatively low measuring frequencies (< 10 Hz) [KOEL08, p. 69].

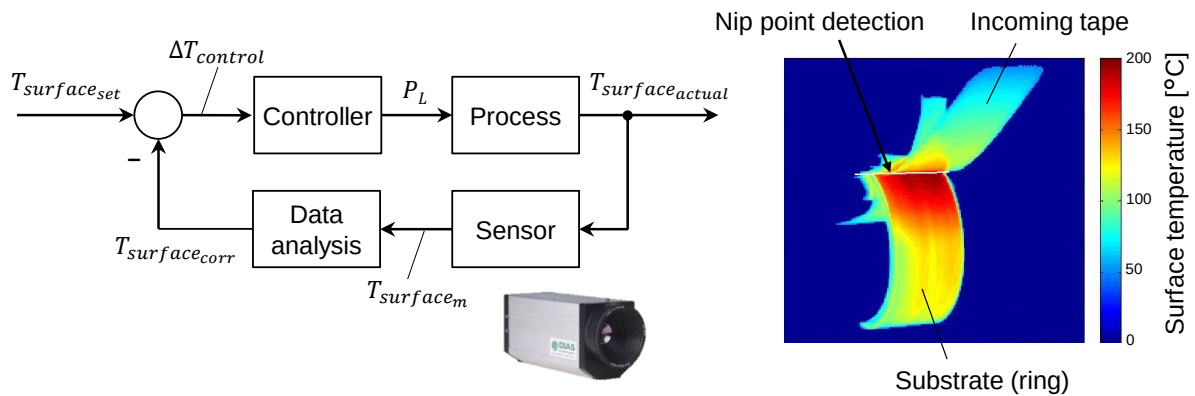


Figure 2.16: Principle of closed-loop control (left) and contact-free surface temperature measurement by infrared camera for a winding process (right) [DIAS17]; adapted from BRECHER et al. [BREC16]

Prinzip der Temperaturregelung (links) und kontaktlose Messung der Oberflächentemperatur mittels Infrarotkamera bei einem Wickelprozess (rechts)

More recently, the use of (uncooled) infrared cameras was introduced, which obtain more spatial temperature information of the process zone, with measuring frequencies of up to 70 Hz. While the nip point is rather difficult to be accessed by single pyrometers, infrared cameras can provide spatial information of the temperature development along the feed direction and derive the nip point position (and temperature) by advanced data analysis [BREC16] [AUGU14b] (Figure 2.16, right-hand side). The data can also be used for process monitoring.

Nevertheless, if the literature statements from Subsection 2.2.4 are true, the *surface* temperature might be an *important* control value for the consolidation process, but not a *sufficient* one. As recently proposed by STOKES-GRIFFIN & COMPSTON, higher placement speeds can change the situation, as a lack of heat soak is supposed to affect the weld strength [STOK15a, p. 279]. Additional thermal preconditions, like the melt dwell time, seem to become increasingly influential at higher speeds, but are *invisible* for current temperature measurement devices.

So far, no feasible (practical) solution exists for online measurements of the through-thickness temperature distribution $T(z)$ without additional efforts, like thermocouples for example. Preparation of the material with thermocouples is costly and time consuming and only feasible in research and development, like in [COME15, p. 12-13] or [KERM15, p. 58]. Knowledge about the heat soak remained mostly hidden so far. Closed-loop controls of the through-thickness temperature profile are not known.

2.4 Weld Strengths at Increased Process Speeds

Fügeschweißfestigkeiten bei erhöhten Prozessgeschwindigkeiten

It is one of the major economic goals of thermoplastic tape placement to achieve high output rates (in kg/hr), while maintaining good mechanical properties. Achieving high *weld strengths* at increased process speed plays a crucial role for reaching this goal (Chapter 1.5). Many investigations have been conducted in order to determine the achievable weld strengths at increased speeds. Before presenting previous results, first some terminology: The *weld strength* appears in the literature in various forms:

- In *absolute* values, like bond/weld strength or interlaminar shear strength (ILSS) or shear strength in [N/mm²] or [MPa]
- In *direct* testing results, like short beam bending testing force, wedge peel force or mandrel peel force in [N]
- In *relative* values, like relative bond/ weld strength or degree of bonding D_B in [0...100%] or [0...1]

Absolute values represent the breaking force F_f projected onto the loaded interface area A_{probe} of the probe. The fracture mechanics of the different testing methods makes it difficult to achieve a common standard here. Especially the high ductility of thermoplastics is an issue. Various testing methods have been applied to measure the shear strength: e.g. the short beam bending test, used by many authors, lap shear test [STOK16b, p. 21-22], wedge peel test [COME14] [COME15, p. 16], mandrel peel test [GROU13], “Lauke” shear test [LAUK92], end loaded spit beam test [GROU13] or the double cantilever test [AGAR96, p. 376].

Direct testing values origin from the raw data of the test. This data can only be used in comparison to results of the same testing setup.

Relative values represent the relation between the actual weld strengths and the maximum achievable strength, which either depends on the maximum strength of the polymer itself, or on the maximum strength of a reference probe, bonded under controlled conditions [STEY13, p. 52]. The *degree of bonding* D_B appears mostly in the context of modelling. The value can be regarded as the *theoretical counterpart* of measured relative weld strength.

It is important to note that high interlaminar shear strengths do not necessarily correlate with other important mechanical properties of the final part, like fracture toughness, flexural stiffness or open-hole compression strength [COME15, p. 15]. However, regarding thermal control it is the most-often discussed value in the literature.

Due to various factors, a relative weld strength of 100% is not achieved in practice. The process speed v_p is one of these factors. Decreasing bonding strengths at increasing process speeds have been reported by many authors. A literature summary was presented in [STOK15a, p. 282]. Figure 2.17 on the next page shows two exemplary findings, for different process speed scales: 0 to 120 mm/s (left side) and 0 to 1400 mm/s (right side).

It can be observed that instead of *one fixed* process speed limit, a *continuous decline* of the weld strength was discovered. This observation holds true for all heating technologies so far, with laser-assisted tape placement being no exception.

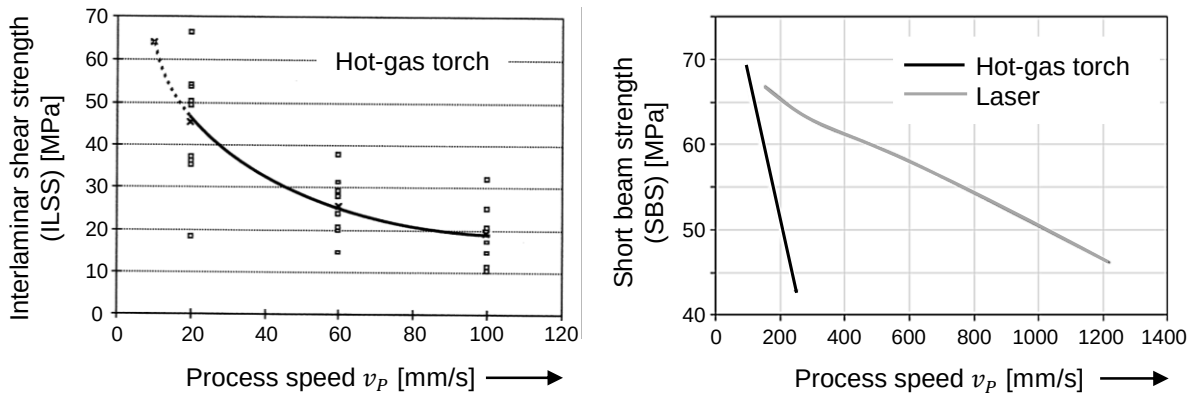


Figure 2.17: Declining weld strengths at increasing process speeds; STEINER for hot-gas-assisted tape placement of PEKK/CF (left), adapted from [STEI96, p. 113] and AUGUST et al. comparing hot-gas- and laser-assisted tape placement for PEEK/CF (right), adapted from [AUGU14b, p. 9]

Abnehmende Fügeschweißfestigkeiten bei erhöhten Prozessgeschwindigkeiten; STEINER für heißgasgestütztes-Tapelegen (links) und AUGUST et al. für heißgas- und lasergestütztes Tapelegen (rechts)

Whereas the declining weld strength in hot-gas-assisted tape placement could be attributed to limited gas temperatures of 800-1000°C (and was predicted by authors) [STEI96, p. 112], the case for laser-assisted tape placement is not so obvious. As STOKES-GRIFFIN & COMPSTON correctly point out: “[...] *Source power no longer imposes a limitation on TP-AFP with modern NIR diode laser sources capable of providing 20 kW output*” [STOK15a, p. 275]. Actually today, several companies do provide laser sources with powers of > 30 kW [LASE13a]. Furthermore, the laser absorption at the surface happens quasi spontaneously at scales < 10⁻⁶ s [BROW10, p. 95]. The speed at which the material moves does not affect the absorption mechanism. This is very different from other heating mechanisms, like convection by hot gas, hot air or flame.

These boundary conditions raise the question whether the laser-assisted tape placement process is limited in terms of process speed at all (regarding thermal aspects). If laser power simply correlates with the consolidation speed, it would be most sensible to use the highest available laser power, because the equipment cost of the laser (per final part weight) increase less than the overall machinery cost (compare Figure 1.7). The economy of laser-assisted tape placement would then depend on the maximum powers, made available by laser builders.

Some authors forecast that with higher process speeds the heat soak is reduced, leading to changing thermal preconditions, which are necessary for a reliable consolidation process (p. 32-33). However, the body of research on this issue is quite limited in the literature. The state of knowledge will be the topic of the following sections.

2.5 Through-Thickness Temperature Distribution

Temperaturverteilung in Dickenrichtung

2.5.1 Determination

Ermittlung

As already mentioned in Section 2.3, the surface temperature has been the predominant control value in thermoplastic tape placement. Predicting this value has been the focus of most heat transfer studies, neglecting the through-thickness temperature distribution for the most part [GROV88] [TOSO92] [STOK15b] [SKAN15].

Most is known about the temperature development within the (mostly) thicker substrate: SONMEZ & HAHN used calculations of the through-thickness temperature development to obtain the crystallization state of the workpiece (Figure 2.19, next page) [SONM97a, p. 218]. KERMER-MEYER correlated the thermal history within the workpiece with residual stresses and warpage [KERM15, p. 45-96].

Investigations of the thermal profile within the *tape* are much more limited in the literature, e.g. in [MODI13]. VOR DEM ESCHÉ proposed an *analytical* model to predict $T(z, t)$ [ESCH01, p. 80], however, the model neglected the heat accumulation which has been observed by others. GROUVE presented his general assumption of the temperature development within the tape in the following way:

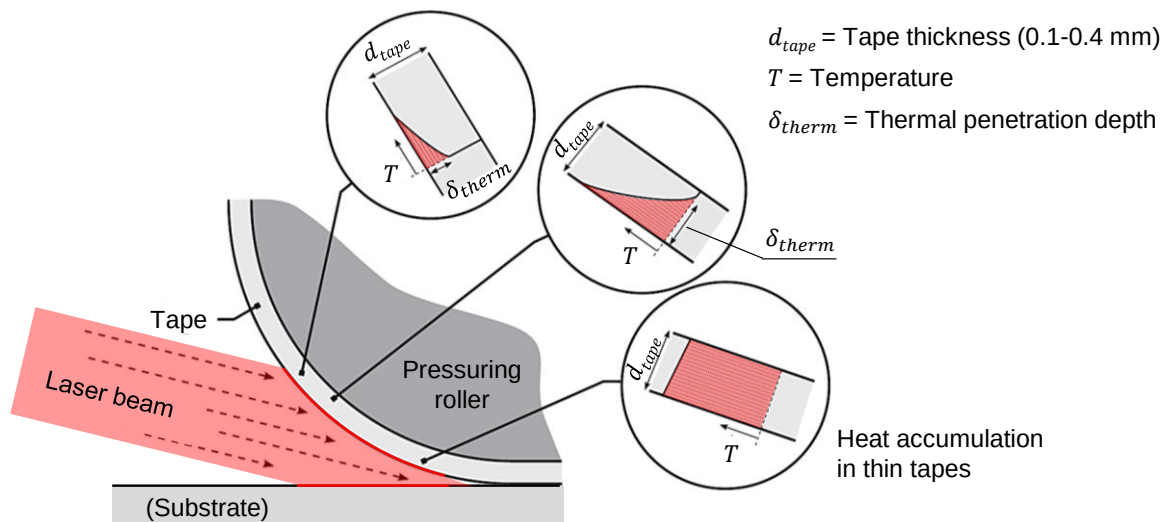


Figure 2.18: Schematic illustration of the temperature profile development in the tape; adapted from GROUVE [GROU12, p. 135]

Schematische Darstellung des sich ausbildenden Temperaturprofils im Tape

At (conventional) tape placement speeds, the heat penetrates the tape and accumulates, when reaching the backside. Many conclusions as such were derived from *numerical* solutions. Gaining practical knowledge about the temperature gradients is therefore rather difficult, unless complex finite element models are implemented. Furthermore, most authors have chosen the *time* domain (or *feed* position) to visualize the temperature development (Figure 2.15). Works that are more recent have

visualized the through-thickness temperature distribution in *pseudocolor images*, e.g. [MODI13] [STOK15b]. In both forms of expression it is difficult to obtain *quantitative* insight on the *time- and position-dependent* temperature development in the thin tapes.

2.5.2 Effect of Process Speed

Auswirkung der Prozessgeschwindigkeit

The predominant focus on the *surface* temperature in heat transfer studies might lead to the prevailing lack of knowledge on the effect of the process speed on the through-thickness temperature distribution. Investigations were mostly conducted for *specific singular* parameter settings and with a focus on the substrate (Figure 2.19), e.g. [SONM97a] [MODI13] [STOK15b]. In principle, graphs like Figure 2.19 can be used to determine the temperature gradients *qualitatively* for specific process speeds (in this case 5 mm/s vs. 50 mm/s). In general, it can be observed that the thermal penetration decreases at higher process speeds – notice the isotherms of 50°C and 200°C at the nip point position (marked in red). However, the temperature gradients within the *tape* cannot be determined from the graphs and it is difficult to compare them *quantitatively*.

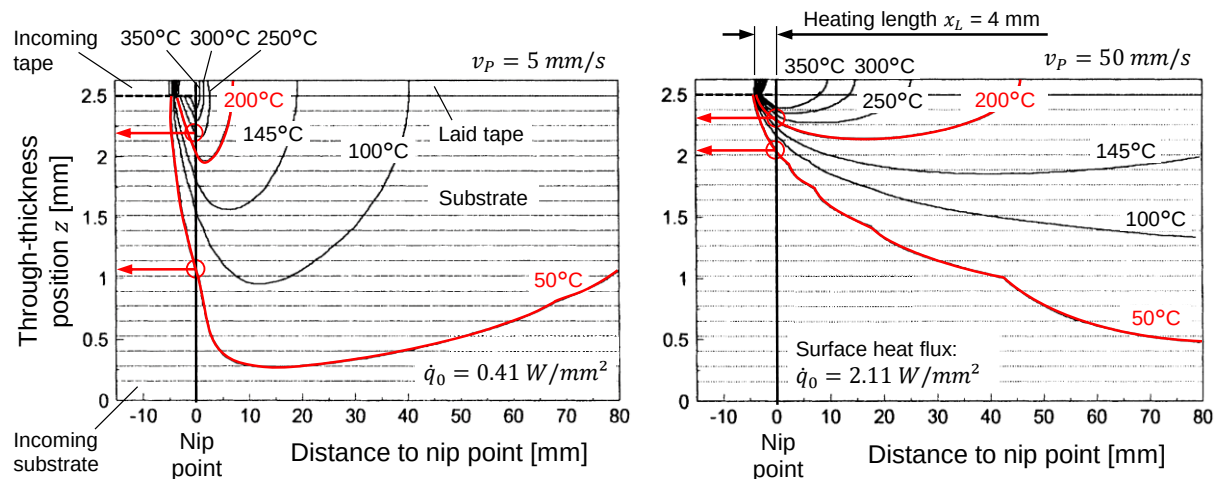


Figure 2.19: Isotherms within a 20-ply laminate during the placement of the 21st layer for two different process speeds. Two isotherms are marked red at the nip point for comparison of thermal penetration; adapted from SONMEZ & HAHN [SONM97a]
Isotherme in einem 20-Lagen Laminat bei der Ablage der 21sten Lage für zwei verschiedene Prozessgeschwindigkeiten. Zwei isotherme sind im Berührungspunkt gekennzeichnet, um die thermische Eindringtiefe zu vergleichen.

GROUVE described the general effect of process speed in the following way: “At *high placement velocities* [...] there will be a distinct skin layer with a high temperature gradient towards the heated surface and a colder back side” [GROU12, p. 135]. The conclusion was derived from the proportionality of the thermal penetration depth δ_{them} and the decreasing irradiation time t_L at higher speeds v_p , from [BEJA03, p. 981]. The first study on the explicit correlation of process speed and through-thickness temperature distribution has been presented only recently in [WEIL17, p. 16]. However, a holistic understanding of the process speed effect on $T(z)$ is still missing.

2.5.3 Effect on the Placement Process

Wirkung auf den Ablegeprozess

Decreasing weld strengths at higher speeds have been reported by several authors (Section 2.4). However, not much is known about the role of increasing temperature gradients (/ decreasing heat soak) in this phenomenon. The first specific investigation on the impact of the heat soak was presented by STOKES-GRIFFIN & COMPSTON in 2015. It was shown that different placement rates (100 mm/s and 400 mm/s) led to varying bond strengths, despite equal surface temperatures. The conclusions of their findings were presented in Subsection 2.2.4, p. 31 [STOK15a]. These recent statements support the hypotheses made several decades earlier by AGARWAL et al. and SONMEZ & HAHN on the possible positive aspects of prolonged preheating.

COMER et al. found that high cooling rates – an inevitable consequence of lower heat soak – lead to lower levels of crystallinity in the bond interface, which is expected to affect the mechanical properties of the part significantly [COME15, p. 15]. Other authors have shown that rapid cooling leads to a weaker fiber-matrix interface strength, because of a thinning of the trans-crystalline region [GAO00a, p. 517].

For the most part, the relevance of the heat soak and temperature gradients has been discussed only *qualitatively* (Subsection 2.2.4). VOR DEM ESCHÉ, for example, recommends the melting of the tape to “[...] *at least 50-60 μm , as boundary conditions for the manufacturing of high-quality laminates*” [ESCH01, p. 85]. The conclusion was drawn from observations made in experiments. However, no general correlations were presented and no method to determine the melt pool depth was described.

Finally, no publication is known that focused specifically on the correlation between $T(z)$ and the weld strength. The negligence of the thermal state in tape placement is startling, considering that other thermoplastic bonding processes have been investigated thoroughly in this domain – compare for example the research done in laser transmission welding [SCHU02, p. 74-90] [WANG14, p. 347], hot-plate welding of plastic pipes [DICK14, p. 13] [TWI17], induction welding of thermoplastic composites [HUEM14] or in the heating, forming and backmolding of thermoplastic composite sheets [EGGE11, p. 42] [LESS14] [EMER14, p. 16] [KLIN15, p. 14-19] [KUGE16].

2.6 Conclusions from the State of the Art

Fazit aus dem Stand der Technik

The state of the art analysis revealed a predominant focus on the surface temperature in thermoplastic tape placement in industry and research. This applies for the so far presented thermal *investigations* as well as for the implemented *temperature control systems* in placement heads. The focus on the surface temperature is plausible, as it is the most critical value for a reliable bonding process with high weld strengths. Nonetheless, as other bonding processes for thermoplastics show, the temperature distribution in through-thickness direction can oftentimes not be neglected, as it can

influence the process in a variety of aspects. Several circumstances may have led to the negligence of the through-thickness temperature distribution in tape placement:

- Within the (comparably thin) tapes, temperature gradients only become significant at combinations of very high speeds and very high laser powers, as will be shown later (Subsection 5.1.1).
- There might have been a lack of equipment to induce these conditions; either a lack of high-power laser sources or limited dynamics of manipulator systems.
- Practical difficulties of measuring and resolving the through-thickness temperature distribution $T(z, t)$ at geometrical scales below $250\text{ }\mu\text{m}$ (*< quarter of a millimeter*) and time scales shorter than 100 ms (*< tenth of a second*)
- High simulation efforts for the determination of the *transient* heat transfer process in the through-thickness direction
- *Predominant focus* on the resulting *surface* temperature instead of the underlying temperature distribution, because the surface temperature is the most critical control value for consolidation.

Gaps in the Literature and State of the Art

Previous works at the Fraunhofer Institute for Production Technology (IPT) have also focused on the computation of the *surface* temperature for *specific laser systems*, like in [SCHM94] [ESCH01] [KOEL08] [STEY13] and [STIM14]. The conducted thermal analyses in these works considered already the time-dependent (transient) through-thickness temperature distribution $T(z, t)$, however, only *specific singular* parameter settings. The main objective was to predict the achievable process speed for a desired surface (melting) temperature, with the available laser equipment.

So far, no *holistic theory* has been presented, starting from the laser irradiation distribution to the final weld strength with a focus on the transient through-thickness temperature distribution $T(z)$. Such knowledge is a key enabler for the *targeted utilization* of novel (adjustable) laser technologies, like VCSEL. Systems that are capable of controlling the final $T(z)$ are missing in the state of the art.

In the field of *analysis of $T(z, t)$* , a lack of *practical computation tools* was found, which impedes efficient and fast predictions. So far, only numerical tools have been capable of computing the process in sufficient accuracy, but require elaborate software accompanied by time-consuming programming efforts. Furthermore, no *experimental setup* is known capable of bonding tapes at *various temperature gradients* and *process speeds* in a controlled manner. This impedes *efficient investigations* of the issue.

It was also noticed that *no real definition* exists for the *thermal penetration* (“heat soak”) in thermoplastic tape placement and no definition of how it should be *measured* in *practice*. A general effect of the heat soak on the weld strength has been demonstrated by STOKES-GRIFFIN & COMPSTON for the first time in 2015, but the body of knowledge is still very thin and the topic is widely ignored.

3 Objectives, Tasks and Outline

Zielstellungen, Aufgaben und Aufbau der Arbeit

3.1 Objectives and Tasks

Zielstellungen und Aufgaben

The state of the art analysis presented correlations among several control parameters and thermal process conditions: Increasing the process speed does affect the through-thickness temperature distribution and it was theorized that the heat soak – an attribute of the temperature distribution – is supposed to affect the weld strength in different possible ways (e.g. by the melt dwell time or cooling rate). It is known that the heat soak can be influenced – at least in principle – by the surface heat flux distribution. Novel laser technologies, like semiconductor lasers or motorized zoom homogenizers, enable online adjustments of the intensity distribution, which opens up new potentials for optimization in thermal control.

It is now of interest to know whether the observed declining weld strengths at higher process speeds can be influenced positively by adjustable laser technologies, like VCSEL. Investigating this possibility – and the relevant cause-and-effect relations – is the objective of this thesis. The theoretical framework structures in the following way:

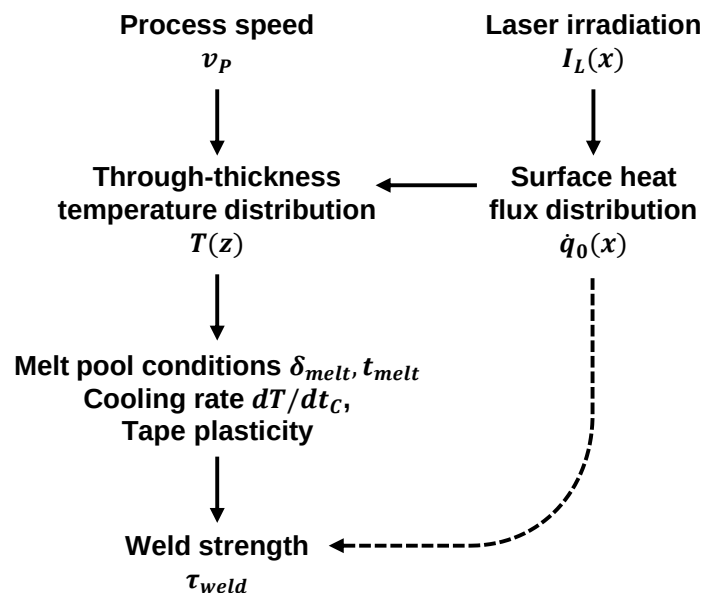


Figure 3.1: Theoretical framework of this thesis: Influence of the weld strengths at high process speeds by use of lasers with adjustable intensity distribution

Theoretischer Rahmen dieser Arbeit: Beeinflussung der Fügenschweißfestigkeiten bei hohen Prozessgeschwindigkeiten durch Nutzung von Lasern mit einstellbarer Laserintensitätsverteilung

The most important objective of the thesis is to deepen the understanding of the temperature distribution in the through thickness direction; how it develops over time at different process speeds and how it affects the consolidation process in detail.

Five interrelated hypotheses will be discussed, of which some have been mentioned qualitatively by previous authors:

- 1) Increased process speeds lead to a *significant* change in the through-thickness temperature distribution (the predicted “skin layer” by GROUVE [GROU12, p. 135])
- 2) High temperature gradients at higher process speeds can influence the weld strengths (proposed by STOKES-GRIFFIN in [STOK15a])
- 3) Fundamental (thermal) limitations exist for conventional tape placement systems with *fixed* laser spots of *homogeneous* irradiation
- 4) The limitations are predefined by the thermal diffusivity of the material, by the irradiation length and intensity distribution (as well as material properties, like reptation time, surface roughness and tape thickness)
- 5) The temperature profile $T(z)$ can be influenced by an adjustable laser irradiation – either by the irradiation *length* or by the laser intensity *distribution*

In view of the findings from the literature, one might be tempted to propose a *complete melting* of the tape by long preheating devices, in order to enable reliable consolidation at high speeds. However, the complete melting of the tape through its thickness comes with drawbacks, preventing positive aspects of *local melting* to be utilized, like high energy efficiency, low void rebound or lower shape distortion by thermal stresses. A summary of the identified pros and cons are documented in the Appendix, Table 14.1.

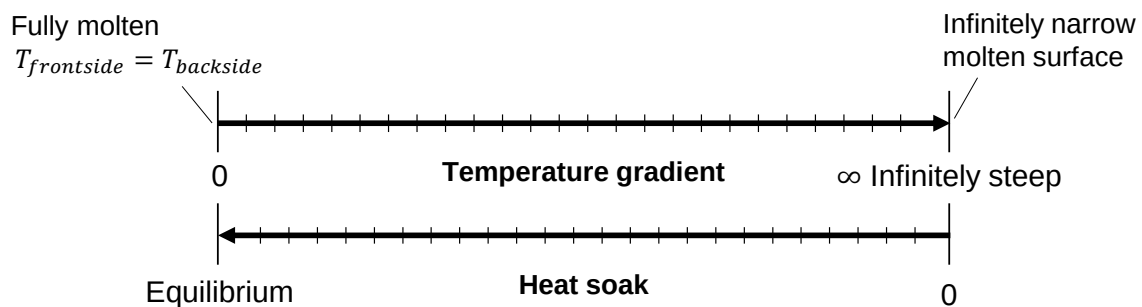


Figure 3.2: Spectral view of the thermal state within fiber-reinforced thermoplastic tapes before bonding. What is the optimal state for a given tape? How can the thermal state be described, measured and how controlled?

Spektrale Sichtweise auf den thermischen Zustand in faserverstärkten Thermoplast-Tapes vor dem Fügen. Was ist der ideale Zustand für ein gegebenes Tape? Wie kann er beschrieben, gemessen und wie gesteuert werden?

In this thesis, the heating of a tape is viewed on a spectrum, beginning from homogeneously molten throughout its thickness at the one end ($\rightarrow 0$), to infinitely narrow molten at the other end ($\rightarrow \infty$), (Figure 3.2). By taking this view, the concept of the *ideal through-thickness temperature distribution* comes to mind and the question how it can be controlled? Which tape properties play a role for the ideal temperature distribution? The work in hand tries to move closer in understanding and answering these questions.

From the five hypotheses mentioned above, the objectives of this thesis with its tasks derive as follows:

Tasks	Objective 1. Developing efficient tools for the determination of the temperature distribution in through-thickness direction:
	- Modelling of the heat transfer during heating and cooling - Derivation of analytical solutions of the thermal problem - Derivation of numerical solutions of the thermal problem - Investigation of the model accuracies - Validation by experiments
	Objective 2. Investigating the through-thickness temperature distribution at increasing process speeds:
	- Investigations by use of analytical solutions - Investigations by use of the numerical solutions - Investigations by experiments
	Objective 3. Theoretical analysis on the influence of the temperature distribution on the weld strength and placement process in general:
	- Consideration of known bonding mechanisms (autohesion, intimate contact development, formability, etc.) on their sensitivity to temperature gradient - Derivation of predictions on the limits of current tape placement systems - Derivation of requirements on the heat soak and the tape attributes
	Objective 4. Experimental investigation on the influence of the temperature distribution on the weld strength:
	- Development of an experimental setup for defined setting of thermal profiles - Development of an experimental setup for the defined bonding of different thermal profiles and different consolidation speeds - Shear strength testing of the weld zones
	Objective 5. Investigation of irradiation strategies:
	- Identification and evaluation of irradiation strategies - Modelling of the influence of the heating length on the thermal profile
	Objective 6. Derivation of a machine concept for controlled thermal profiles:
	- Conception of a machine for controlled heating lengths - Predesign of the machine

Figure 3.3: Objectives of this thesis with resulting tasks
Ziele dieser Arbeit mit resultierenden Aufgaben

As materials, PEEK/CF will be considered for investigations of the transient heat transfer, due to the available data in the literature. The material will also be used for the *analytical* and *practical* investigations of the influence of temperature gradients on the bonding process. For *practical* investigation of the bonding process itself, HDPE/GF will be used. The material properties are documented in the Appendix, Chapter 18.

3.2 Outline

Aufbau der Arbeit

The outline of the thesis bases on the cause-and-effect chain in laser-assisted tape placement (Figure 3.4): beginning from the surface heat flux distribution $\dot{q}_0(x)$, along the through-thickness temperature distribution $T(z)$, to the final strength of the weld τ_{weld} . Optical phenomena will explicitly not be considered for the purpose of *generalization*. The variety of systems in the market makes it difficult to obtain universal knowledge, because optical phenomena do strongly depend on the specific machine setups, like the chosen roller diameter/deformation, type of laser, laser angle, tape infeed angle or the part geometry (Section 2.1).

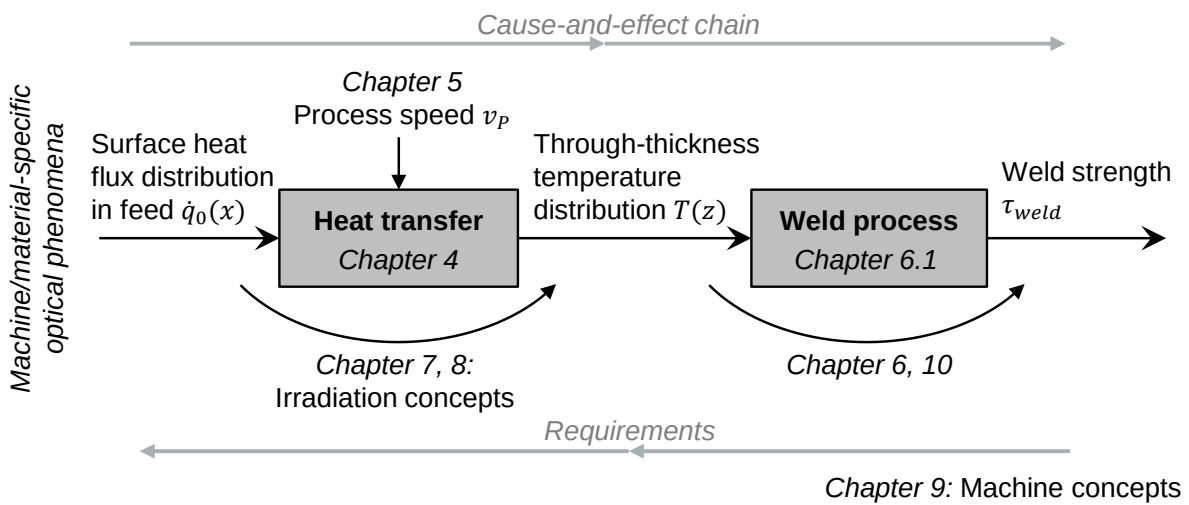


Figure 3.4: Outline of the thesis
Aufbau der Arbeit

At the beginning in *Chapter 4*, the transient thermal model will be introduced for the prediction of time-dependent temperature distributions $T(z, t)$. The model is designed to reach adequate predictions for practical purposes and enable analytical solutions of the problem. The chapter is mainly based on a prepublication [WEIL17]. *Chapter 5* will use the model to investigate the final temperature distribution at varying process speeds. It will be examined how the temperature distribution develops over time and how the resulting thermal condition affects welding preconditions, like melt pool dwell time/length /depth, cooling rate and tape plasticity. *Chapter 6* will analyze the known bonding mechanisms, like autohesion and surface contact development, for how the temperature distribution can affect the weld formation. A novel experimental setup will be presented for the bonding of tapes with defined temperature gradients and process speeds. It will be investigated how the gradients affect the weld strength. The relevance of tape properties will be discussed. *Chapter 7 and 8* will present possibilities to control the temperature distribution by appropriate irradiation. The influence of the heating length will be described in detail. Finally, *Chapter 9* will propose novel winding machine concepts for controlled irradiation, based on VCSELs and zoom homogenizers. An optimization strategy for the melt dwell length is addressed in the last *Chapter 10*.

4 Determination of the Temperature Distribution in Through-Thickness Direction

Ermittlung der Temperaturverteilung in Dickenrichtung

In order to investigate (and eventually control) temperature profiles $T(z)$, it is first and foremost of interest to predict them. This will be the topic of this chapter. In recent decades, several heat transfer models for laser-assisted tape placement have been proposed and have been used for process investigations. A comprehensive review was presented recently in [ORTH17]. The so-far presented models can be distinguished by whether they have been solved analytically or by numerical methods.

Analytical solutions for laser-assisted tape placement have been presented by GHASEMI NEJHAD et al. [GHAS91], SCHMIDT [SCHM97, p. 46-50] VOR DEM ESCHÉ [ESCH01, p. 80] and DAI & YE [DAI02]. Succeeding authors, like STEYER and STIMPFL used the previously introduced models to investigate material- and system-specific heating processes [STEY13, p. 50] [STIM15, p. 61-63].

Numerical models for laser-assisted tape placement have been presented by GROVE [GROV88], BEYELER & GÜÇERİ [BEYE88], SONMEZ & HAHN [SONM97a], AGARWAL et al. [AGAR92], KOELZER [KOEL08, p. 57-59], GROUVE [GROU12, p. 30-34], MODI et al. [MODI13, p. 2] and STOKES-GRIFFIN & COMPSTON [STOK14] [STOK15b]. The models of JAMES & BLACK and TOSO & ERMANNI have to be named here as well, because both were implemented for infrared-assisted tape placement, which is also a radiation-based heating method [JAME96] [TOSO04]. It can be concluded that the majority of authors turned to numerical methods for heat transfer analysis.

The so-far mentioned models vary significantly in their complexity and considered boundary conditions. Whereas the model of VOR DEM ESCHÉ only includes the average surface heat flux $\dot{q}_0$ and laser irradiation time t_L , the models of STOKES-GRIFFIN & COMPSTON include optical phenomena (like reflection), the geometrical effect of roller deformation and non-linear temperature-dependent material properties.

The models also vary considerably by the modelled heat flows. Whereas TOSO & ERMANNI modelled the heat flow in all three dimensions (width, feed and through-thickness), GROUVE simplified the analysis to the heat flow in the thickness direction, which many authors confirm to be most-relevant for the prediction of the surface temperature [COLT92, p. 428] [TIER06, p. 1490] [GROU12, p. 30]. GROUVE also initially modelled heat losses by convection and radiation, but later mentions that these heat loss terms are insignificant for the calculation of energy efficiency [GROU12, p. 134]. VOR DEM ESCHÉ came to similar conclusions [ESCH01, p. 81-84].

Because model *complexity* is not a quality attribute in itself – and can be distracting from the crucial physical phenomena – the following sections will also investigate, which of the previously made simplifications can be applied, but still yield good-enough results for practical purposes. The aim is to reduce the transient thermal problem to an analytically solvable one and to investigate the resulting *prediction accuracy*.

4.1 Description of the Heat Transfer Problem

Beschreibung des Wärmeübertragungsproblems

This section presents the heat transfer problem in a comparably high degree of detail. Simplifications will be explained later. The area of interest of the transient heat transfer analysis is depicted in Figure 4.1. The figure shows the principle boundary conditions of the laser-assisted tape placement process by the example of a tape winding setup:

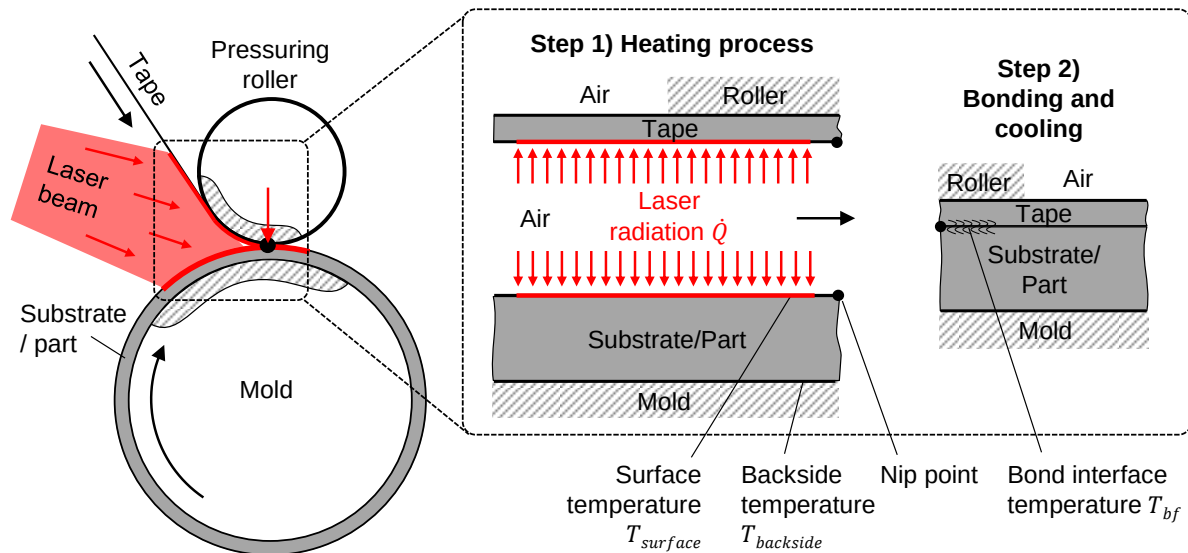
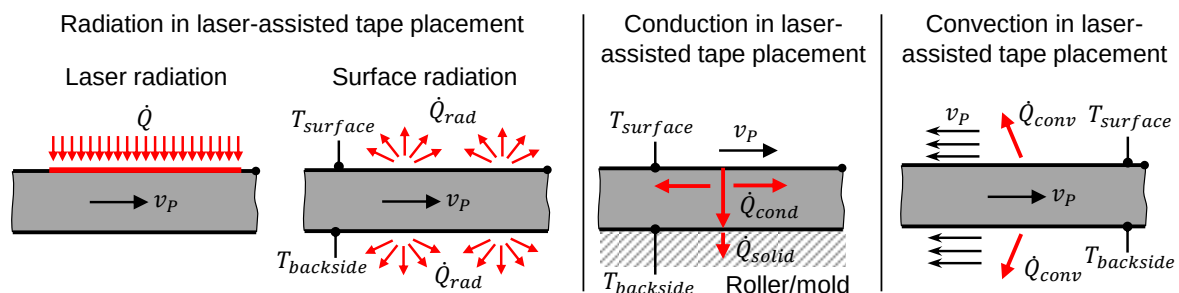


Figure 4.1: Area of interest of the transient heat transfer analysis: heating and subsequent cooling of the bond interface (schematically drawn)

Untersuchungsgegenstand der transienten thermischen Analyse: Erwärmung und anschließende Auskühlung der Fügefläche (schematische Darstellung)

Several *heat flows* do (in principle) occur and are subsequently presented: Radiative heat flow into the bodies by the laser (**Heat flow 1**); conductive heat transfer in width direction (**Heat flow 2**); conductive heat transfer in fiber direction (**Heat flow 3**); conductive heat transfer in the through-thickness direction (**Heat flow 4**); radiation and (forced) convection from the surface to the environment (**Heat flow 5**) as well as heat transfer between tape and pressing roller (**Heat flow 6**) and between substrate and mold (**Heat flow 7**). After contact, tape and substrate exchange heat (**Heat flow 8**).



cond: conduction, *conv*: convection, *rad*: radiation

Figure 4.2: (Principle) heat flows in laser-assisted tape placement
(Prinzipielle) Wärme-flüsse beim lasergestützten Tapelegen

Besides the heat flows, several *thermal aspects* exist that can complicate the problem: For example, when the tape gets into contact with the substrate, a local heat transfer resistance R_c occurs between tape and substrate, due to the surface roughness. It rapidly vanishes by the intimate contact development (**Thermal aspect 1**).

The convective heat flow $\dot{Q}_{conv}(T)$ is temperature-dependent. Its coefficient depends on the speed and characteristic length $h_{conv}(v_p, x_L)$ [LATR03, p. 77] [BERG11, p. 390] (Figure 19.4, p. 195) (**Thermal aspect 2**); the radiant heat flow $\dot{Q}_{rad}(T)$ and the radiation coefficient $h_{rad}(T)$ are both temperature-dependent (**Thermal aspect 3**).

Tape and substrate are anisotropic regarding their thermal conductivity k . The tape is roughly 8-10 times more conductive in the fiber direction (k_x), compared to the width and thickness direction (k_y, k_z) – for the case of carbon fiber tapes [KOEL08, p. 48]. The direction of highest conductivity of the substrate depends on the previously laid fiber directions (**Thermal aspect 4**). Tapes consist of fibers and matrix, so the heat flow at the micro level can (in principle) be locally different (**Thermal aspect 5**). Furthermore, it is difficult to manufacture tapes with perfectly homogeneous fiber *distributions*, which leads to a certain inhomogeneity of material properties along the thickness (and width), like thermal conductivity $k_z(z)$ (**Thermal aspect 6**). Further, both thermal conductivity $k(T)$ and specific heat capacity $c_p(T)$ are temperature-dependent material properties [GROV88] [ESCH01, p. 66] [KOEL08, p. 48] (**Thermal aspect 7**).

Both tape and substrate are not perfectly flat, but slightly curved in the feed direction, which could (in principle) influence the heat transfer as well (**Thermal aspect 8**) [BEJA03, p. 181]. In many process conditions, the heated bodies (tape/substrate) are *finite* in their thermal behavior, meaning that heat can reach the back of the body and accumulate [GROU12, p. 134-136] (**Thermal aspect 9**).

The *latent heat of fusion* and *crystallization* of the polymer can lead to heat sinks and sources during the heating/cooling phase [BEJA03, p. 1273]. The magnitude of latent heat depends on the heating and cooling *rate* [KOEL08, p. 49] (**Thermal Aspect 10**).

Furthermore, the degree of intimate contact among the previously laid tapes can create inter-layer contact resistances $R_{inter-layer}$. This can retard the heat to flow inwards into the substrate, leading to heat accumulation and potential overheating at the upmost layers [LEVY14] (**Thermal aspect 11**).

The substrate can also store the heat for a certain period of time, remaining elevated until successive laying processes; it can also be preheated by the mold [KERM15]. The initial temperature of the substrate T_i before bonding can therefore vary significantly throughout the part manufacturing process (**Thermal aspect 12**).

The laser irradiation time t_L can change during the manufacturing process, depending on the tape speed control or the process situation, e.g. during start and stop, or when the manipulator – mostly a robot – has to slow down before passing a significant geometrical change [KOLL16, p. 5], e.g. Figure 2.13, p. 30, (**Thermal aspect 13**).

Previous authors have shown that a surface heating until the nip point is not possible in laser-assisted tape placement. Optical phenomena prevent this request, because of increasing incidence angles along the roller path, reflection and the formation of a shading area. These effects depend on the geometry of the roller and the substrate, the laser angle, tape infeed angle as well as the reflection coefficients of the materials. [GROV88] [KOEL08, p. 59] [STOK14] [WEIL16b] As a consequence, the heat flux distribution $\dot{q}_0(x)$ at the material surface is not homogeneous during the last stretch of the heating zone (**Thermal aspect 14**) and the shading effect leads to a certain distance of non-irradiated material (**Thermal aspect 15**).

Depending on the material transmittance τ , the laser can also penetrate the material to a certain degree, leading to volumetric absorption $\dot{q}_0(z)$ instead of surface absorption [STIM14, p. 53-55] (**Thermal aspect 16**).

Consideration of the heat flows yields to the following equation:

$$\rho c_p(T) v_p \frac{dT}{dx} = k_x(T) \frac{d^2T}{dx^2} + k_{zy}(T) \frac{d^2T}{dy^2} + k_{zy}(T) \frac{d^2T}{dz^2} + \rho r; \quad v_p = \frac{dx}{dt} \quad (4.1)$$

with ρ as the material density, $c_p(T)$ as the temperature-dependent specific heat capacity, v_p being the process speed and $k_x(T), k_{zy}(T)$ being the temperature-dependent thermal conductivities in fiber and thickness/width direction.

The term r represents the heat source term of the crystallization process. Detailed explanations on the term are given in [SONM97a, p. 205]. The latent heat of fusion has been modelled via the temperature-dependent heat capacity $c_p(T)$ [LAMB04].

Furthermore, the following boundary conditions can be considered for the heat flux by the laser and the heat losses by radiation and convection at the surface (front side):

$$-k \frac{dT}{dz} \Big|_{z=0} = \dot{q}_0(x, t) - h_{conv}(v_p) \cdot [T_0 - T(0, t)] - h_{rad}(T) \cdot [T_0 - T(0, t)], \quad (4.2)$$

not considering the laser penetration $\dot{q}_0(z)$ in the thickness direction.

The following boundary conditions apply to the backside (Figure 4.6, p. 55):

$$\begin{aligned} -k \frac{dT}{dz} \Big|_{z=d} &= -h_{conv}(v_p) \cdot [T_0 - T(d, t)] - h_{rad}(T) \cdot [T_0 - T(d, t)] - h_{solid}(T) \\ &\quad \cdot [T_{solid} - T(d, t)] \end{aligned} \quad (4.3)$$

The convective coefficient $h_{conv}(v_p, x_L)$ depends on the speed (and characteristic length) at which the material moves through the surrounding air [LATR03, p. 77] and the radiative heat transfer coefficient $h_{rad}(T)$ is temperature-dependent.

An analytical solution to this parabolic differential equation with all considered thermal aspects is difficult to obtain. No such attempt will be made. Instead, a *numerical* model will be presented, which includes most of the heat flows and thermal aspects, except for optical ones. Thereafter, model simplifications from the literature will be reviewed to reduce the problem to an *analytically solvable* one. This model will then be qualified against the (more detailed) numerical model and will later be validated by experiments.

4.2 (Detailed) Thermal Model with Numerical Solution

(Detailliertes) Thermisches Modell mit numerischer Lösung

After tape and substrate got into contact, they exchange heat. Finite element (FE) models can compute this inter-body heat flow in detail. FE models also enable consideration of the more complex material properties, like *latent heat of fusion*, *crystallization* as well as the *temperature-dependent* specific heat capacity $c_p(T)$ and thermal conductivity $k_z(T)$. Heat flows out of the bodies can be considered as well, like convection $\dot{Q}_{conv}$, radiation $\dot{Q}_{rad}$ and heat flows to the roller/mold ($\dot{Q}_{roller}/\dot{Q}_{mold}$). Moreover, speed- and temperature-dependent coefficients can be modelled, like $h_{conv}(v_P, x_L)$ and $h_{rad}(T)$. All considered boundary conditions are shown in Figure 4.4 (next page) and are listed in Table 4.3 (left row). Optical aspects are neglected in this thesis but are still documented in Table 4.3 for the sake of completeness. The specifics of the thermal coefficients are described in the Appendix (Section 19.4 and 19.5).

Geometrical Design. Figure 4.3 depicts the geometrical design of the FE model. The model uses the fact that the heat flow in fiber direction has no significant influence on the process at speeds above 50 mm/s [GROV88, p. 368-369] [COLT92, p. 428] [TIER06, p. 1490]. Prestudies conducted for this thesis confirmed this assumption (Figure 16.2, p. 182, Figure 21.1). At speeds > 50 mm/s, the impact on $T_{surface} < 1.5\%$.

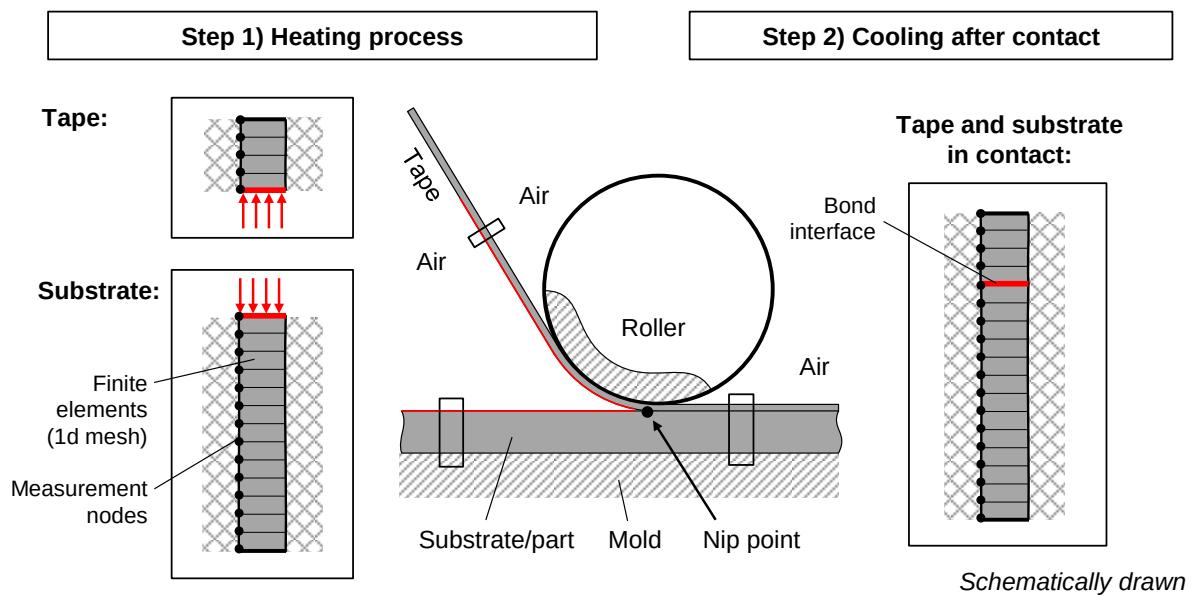


Figure 4.3: Geometrical design of the finite element model for analysis of the through-thickness temperature distribution before and after contact of tape and substrate. Please consider in combination with Figure 4.4 and Figure 21.1, p. 201 *Geometrischer Aufbau des Finite-Elemente-Modells zur Analyse der Temperaturverteilung in Dickenrichtung vor und nach Kontakt von Tape und Substrat. Betrachten Sie bitte in Kombination mit Abb. 4.4 und 21.2, S. 201*

A finite element thickness of $10\ \mu\text{m}$ was found to be sufficiently thin for a high resolution of $T(z)$. Width and length of the elements were found to be irrelevant. The element meshing was verified according to standard FE guidelines in [DASS14, p. 453].

Process Flow. The computation is separated in two steps: (1) a heating phase and (2) a cooling-after-contact phase: During the heating phase, the *finite elements* of the tape and substrate are already connected, but thermally insulated against each other. The insulation is later removed when the tape contacts the substrate in the time domain (emulating the nip point); this is the beginning of step (2):

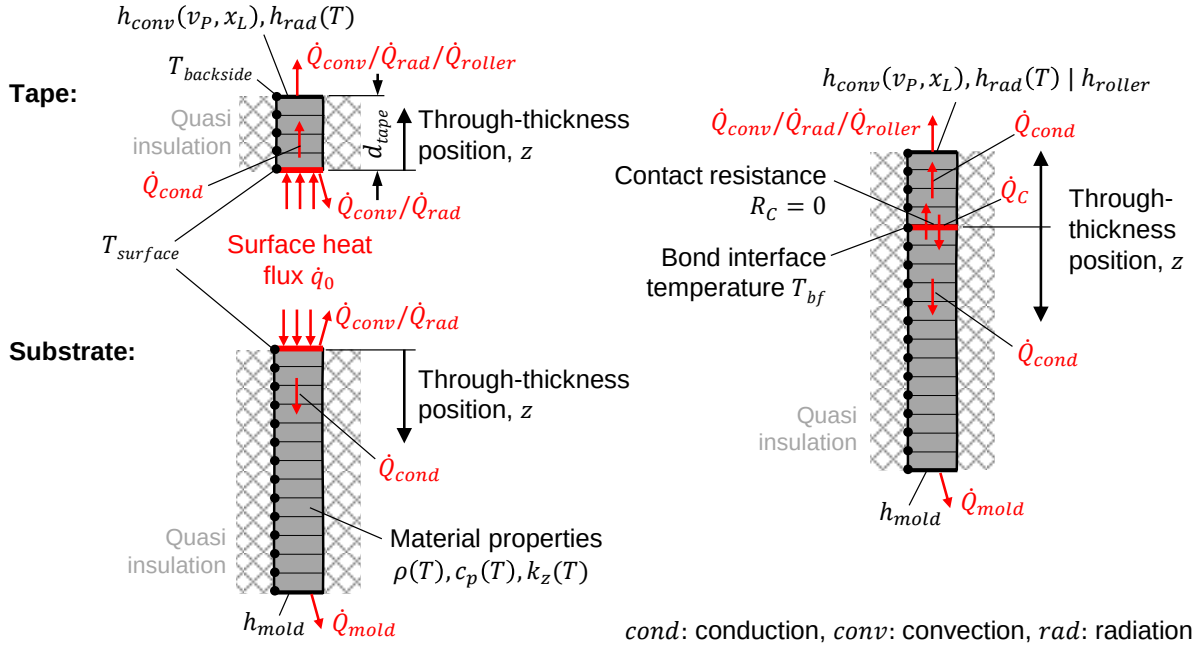


Figure 4.4: FE model with considered boundary conditions
FE-Modell mit betrachteten Randbedingungen

The modelling approach differs from previously presented numerical models, which have considered tape and substrate by *mass flows* with accompanying *finite element contacting* at the nip point, e.g. [TOSO92] [STOK14, p. 108] [STOK15b, p. 1152]. These aspects make the practical implementation much more complex and increases the computing time significantly. The presented modelling approach reduced the computation time by several orders of magnitude (Table 4.4).

Two versions of the numerical model were implemented:

- **Detailed** version, as described in the previous pages. This version includes most of the described heat flows and thermal aspects from Section 4.1
- **Simplified** version, which holds the same assumptions as a simplified analytical model that will be presented in Subsection 4.3.1, Table 4.3 (right row). The simplified numerical version however considers the heat flow among tape and substrate after contact $\dot{Q}_C$, to investigate the bond interface cooling, Table 4.3 (middle row).

The detail numerical model will later be used to assess a simplified models (Subsection 4.3.2) and to quantify the errors that come with the simplifications made in the literature so far. For exemplary results, see forward to Figure 5.4 / Figure 5.5, p. 77. Here, the time-dependent heating and cooling process of different process speeds is shown.

4.3 (Simplified) Thermal Model with Analytical Solutions

(Vereinfachtes) thermisches Modell mit analytischen Lösungen

The complexity and implementation of the presented numerical model made it difficult to generate knowledge in a short period of time for a high number of parameters. Further, many of the thermal aspects were found to have no real significance in the context of investigating $T(z)$ for varying process speeds. In the following subsection, the heat transfer problem will therefore be reduced to its most significant physical phenomena. By this, the problem will be made analytically solvable.

4.3.1 Derivation of the Assumptions Made

Herleitung der getroffenen Annahmen

Prerequisite for a feasible model simplification is a careful analysis of the boundary conditions and a clear definition of the constraints under which the simplified model holds true. Before the assumptions are described, Figure 4.5 defines the coordinate system and the dimensions for consideration. In the following, the term *surface* temperature will be used synonymously for the temperature of the irradiated *front side*.

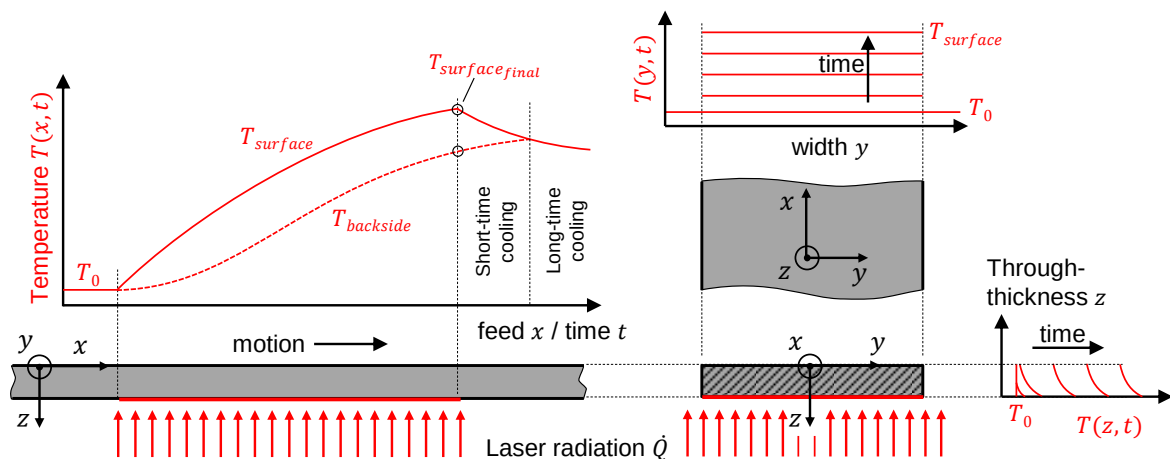


Figure 4.5: Dimension to be considered: feed direction (x), width direction (y), through-thickness direction (z) exemplary for the case of the tape

Zu betrachtende Richtungen: Bewegungsrichtung (x), Breitenrichtung (y), Dickenrichtung (z); exemplarisch für den Fall des Tapes

Heat flow 1. The energy input mechanism of laser heating is fundamentally different from other heating mechanisms, like conductive heating (e.g. by sliding shoes) or convective heating (e.g. by hot gas or flame). In the latter cases, a heat transfer resistance R is present, whereas in laser heating the radiation spontaneously transforms into heat at the material surface by absorption [ESCH01, p. 80]. A thermal resistance does therefore quasi not exist. It is one of the major advantages of laser heating. For deeper description of *the laser-matter interaction*, the author refers to [POPR05, p. 13-39].

Heat flow 2. In most systems, the laser spot is larger than the welding zone (and the tape), overlapping left and right by at least 1 mm, compare Figure 21.1, p. 201. Besides

that, the thermal penetration depth in all directions δ_{therm} is comparably low (< 1 mm), which is why the heat transfer in the width direction can be neglected as well. This has been pointed out by several authors, e.g. [GROU12, p. 30].

Cooling at the tape *edges* has been proven to be negligible already by GROVE [GROV88, p. 369]. This is obvious, considering the high ratios between the heated width (6 mm to 50 mm) and the tape thickness (0.1 mm to 0.4 mm).

Heat flow 3. The thermal diffusivity in the fiber direction is several times higher than in the thickness direction. This has led some authors to include the feed direction into their thermal analyses, which made the models difficult to solve analytically [GHAS91, p. 25-28]. Most authors have therefore turned to numerical solutions.

However, it was already proven in 1988 by GROVE that for elevated process speeds the thermal diffusivity in fiber direction does not significantly influence the through-thickness temperature distribution [GROV88, p. 368-367]. This is because the tape travels much faster (> 50 mm/s) than the heat by internal conduction through the relatively large heating zones (> 20 mm). Successive authors came to the same conclusion [COLT92, p. 428] [TIER06, p. 1490] [GROU12, p. 30]. An analysis, conducted during the course of this thesis, showed that a consideration of the thermal diffusivity in the feed direction changes the result of the bond interface temperature after cooling of 100°C by $< 1.5\%$, for process speeds > 50 mm/s (Figure 16.2, p. 182).

Heat flow 5-7 and thermal aspect 2-4. This paragraph will present a validation of the assumption that the heat losses by radiation, convection and to the roller or mold can also be neglected for the short-time heating and cooling domain – especially for high temperature gradients. First, some relevant values have to be introduced:

The temperature difference between the tape and its environment $\Delta T_{tape \rightarrow 0}$, which is obtained by subtraction of the internal tape temperature at the front side and the ambient temperature T_0 , $\approx 20^\circ\text{C}$ (see Figure 4.6 on the next page for clarification).

$$\Delta T_{tape \rightarrow 0} = T_{surface} - T_0 \quad (4.4)$$

This value represents the potential for heat to leave the body (see Equation 4.6). The second important value in our consideration is the temperature difference *within* the body between the heated surface (front side) and the colder backside $\Delta T_{s \rightarrow b}$. This value is obtained by subtracting $T_{surface}$ with the temperature of the backside $T_{backside}$:

$$\Delta T_{s \rightarrow b} = T_{surface} - T_{backside} \quad (4.5)$$

This value points to the potential for heat flow within the body. The temperature difference to the environment $\Delta T_{tape \rightarrow 0}$ increases when the body is heated up; the temperature difference within the body $\Delta T_{s \rightarrow b}$ increases only when temperature gradients occur, which is commonly the case in laser-assisted thermoplastic tape placement. By use of these values, and the consideration of *Newton's Law of Cooling*,

$$\dot{Q} \sim \frac{1}{R} \cdot \Delta T, \quad (4.6)$$

statements can be made about the *general heating and cooling behavior*. For this, the main thermal resistances (R) of the system have to be identified. The subsequent figure shows a thermal resistance network model in a cross section of the tape:

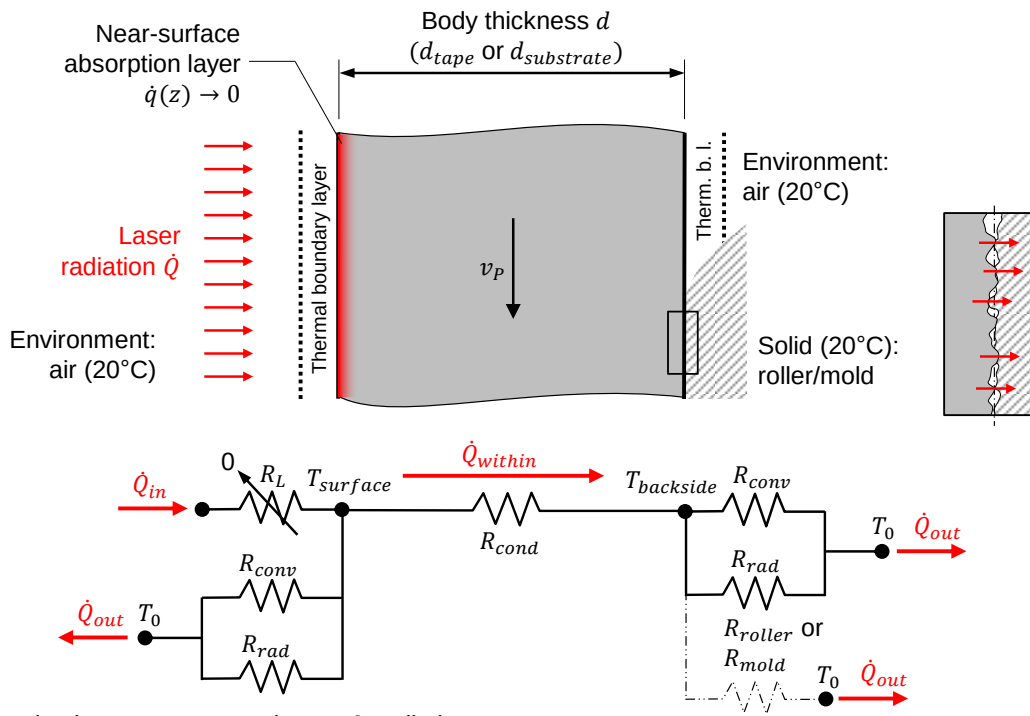


Figure 4.6: Thermal resistance network model of the laser-assisted tape heating process; here exemplary for the case of the tape; please consider in combination with Figure 21.1, (p. 201); values can be compared in Figure 4.7

Thermisches Widerstandsmodell des lasergestützten Tapeerwärmungsprozesses; exemplarisch für den Fall des Tapes; bitte betrachten Sie in Kombination mit Abb. 21.2; die Werte können in Abb. 4.7 verglichen werden.

The thermal resistance *within* the body R_{within} consists only of the thermal resistance by conduction R_{cond} . The thermal resistance out of the body at the *front side* R_{out} consists of a convective and radiative thermal resistance: R_{conv} and R_{rad} . The same holds true for the *backside* of the body. When the tape gets into contact with the roller, the thermal resistance at the backside changes to a thermal resistance to a solid R_{solid} . Regarding heat flows in tape placement we can state:

If the temperature difference between the sides of the tape is much greater than the temperature difference between the surfaces and environment, multiplied by the fraction of the respective thermal resistances, then the heat flow out of the tape is much smaller than the heat flow within the tape (& vice versa).

The same holds true for the substrate. The statement can be written as:

$$\frac{1}{R_{within}}(T_{surface} - T_{backside}) \gg \frac{1}{R_{out}}(T_{tape} - T_0) \Rightarrow \dot{Q}_{within} \gg \dot{Q}_{out} \quad (4.7)$$

It is assumed that because of this correlation, the *heat flows out of the tape* can generally be neglected in laser-assisted tape placement processes – especially at higher speeds. The subsequent pages will present a case for this assumption.

First, the average thermal resistances of conduction, convection, radiation and to a solid (roller/mold) needs to be obtained by:

$$R_{cond} = \frac{L}{\bar{k} \cdot A}; R_{conv} = \frac{1}{\bar{h}_{conv} \cdot A}; R_{rad} = \frac{1}{\bar{h}_{rad} \cdot A}; R_{solid} = \frac{1}{\bar{h}_{solid} \cdot A} \quad (4.8)$$

The parameter L represents the characteristic length to be considered. We will use the typical tape thickness d_{tape} of 0.2 mm. Because we only want to *compare* thermal resistances, the surface area A is set to the universal value of 1 mm².

The parameter $\bar{k}$ is the average thermal conductivity between ambient temperature (20°C) and T_{max} ($\approx 400^\circ\text{C}$), taken from [COGS92, p. 241] (Table 18.1). $\bar{h}_{conv}$ is the averaged heat transfer coefficient to air for the range of process speeds between 0 and 500 mm/s (Table 4.1). $\bar{h}_{rad}$ is the averaged heat transfer coefficient in the range of 20 to 600°C, for a material with an emissivity near $\varepsilon = 1$, which applies for C-FRP. $\bar{h}_{roller}$ and $\bar{h}_{mold}$ represent averaged heat transfer coefficients from the tape to a metallic roller and mold from the literature (conservatively high values were taken).

Table 4.1: Averaged heat transfer coefficients in thermoplastic tape placement

Gemittelte Wärmeübergangskoeffizienten beim Thermoplast-Tapelegen

Property	To environment		To solids	
	Average heat transfer coefficient convection $\bar{h}_{conv}$	Average heat transfer coefficient radiation $\bar{h}_{rad}$	Heat transfer coefficient to roller $\bar{h}_{roller}$	Heat transfer coefficient to mold $\bar{h}_{mold}$
Value	$40 \frac{W}{m^2K}$	$57 \frac{W}{m^2K}$	$150 \frac{W}{m^2K}$	$300 \frac{W}{m^2K}$
Description	Average value for speed range: 0-500 mm/s	Average value for range: 20-600°C; $\varepsilon = 1$	Averaged value from the literature	Averaged value from the literature
Reference	[LATR03, p. 77] (Section 19.5)	(Appendix, Section 19.4)	[LATR03, p. 81-82] [COGS92, p. 112]	[LATR03, p. 81-82] [COGS92, p. 112]

The thermal resistances can be derived by Equation 4.8 and yield to $R_{cond} = 303 \text{ K/W}$, $R_{conv} = 25,000 \text{ K/W}$, $R_{rad} = 17,544 \text{ K/W}$, $R_{roller} = 6667 \text{ K/W}$ and $R_{solid} = 3333 \text{ K/W}$. Radiation and convection have to be set in parallel by [BERG11, p. 118-123]:

$$R_{conv/rad} = \frac{R_{conv} \cdot R_{rad}}{R_{conv} + R_{rad}} \quad (4.9)$$

The thermal resistance out of the body by convection and radiation combined yields to $R_{conv/rad} = 10,309 \text{ K/W}$. Figure 4.7 on the next page summarizes the findings.

It can be observed that the thermal resistance for the heat to leave the tape by convection and radiation is 34 times (!) higher than the thermal resistance from one side of the tape to the other. Even for the case of a contact to a solid, e.g. the roller or mold – with conservatively high values taken –, the thermal resistance out of the body is 11-22 times higher. For all analyzed thermal resistances applies: $R_{out} \gg R_{within}$. It

leads to the general conclusion that heat much rather diffuses from one side of the tape to the other side than to leave the tape by convection, to the roller or to the mold.

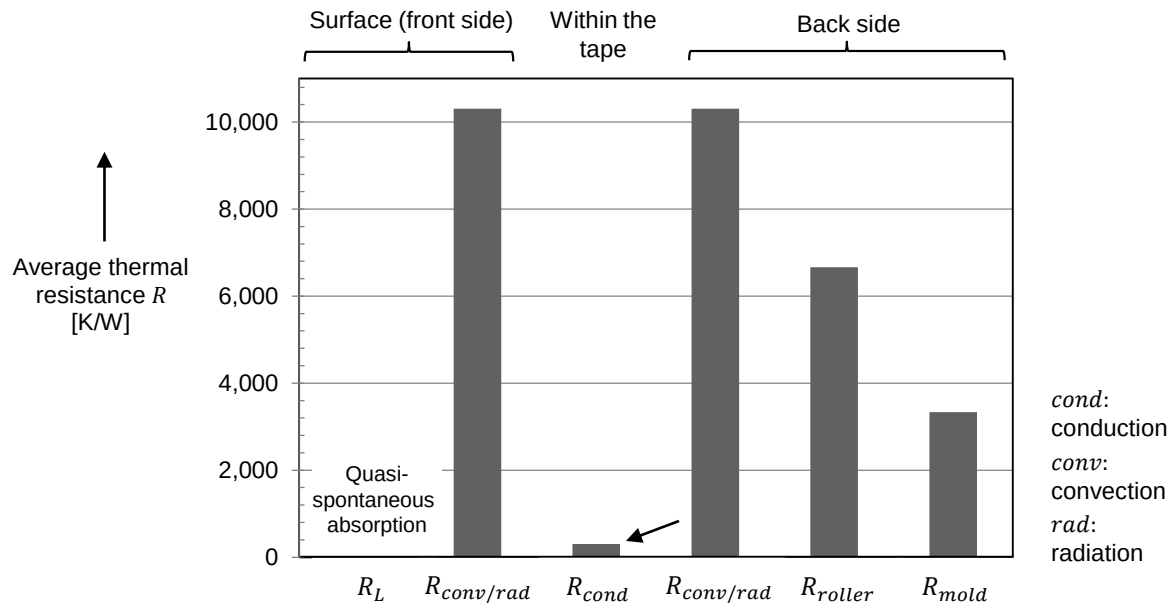


Figure 4.7: Average thermal resistances in laser-assisted thermoplastic tape placement for the exemplary case of a PEEK/CF tape of 0.2 mm thickness

Gemittelte thermische Widerstände beim lasergestützten Tapelegen für den exemplarischen Fall eines 0,2 mm dicken PEEK/CF-Tapes

Furthermore, in case of the tape, the pressurized contact to the roller appears rather *late* during the heating cycle (especially at low tape infeed angles), leaving little time for the backside condition to influence the irradiated surface at all. At this point, the magnitude of the temperature gradient has already established.

Additionally, if the backside of the tape remains solid ($< T_{melting}$), the surface asperities are still rigid and the tape-to-roller heat transfer coefficient $\bar{h}_{roller}$ is consequently even smaller (Figure 5.2, Figure 18.3, p. 189), 50 W/(m²·K) according to [LATR01, p. 79-81].

Lastly, elastic rollers have lower thermal conductivities than the considered metallic roller: 0.18 W/(m·K) compared to 18 W/(m·K) for steel [STOK14, p. 108]. The thermal conductivity of elastomers is 3 times lower than that of a typical tape: $k_{tape} = 0.6-0.8$ W/(m·K). This further retards heat to flow from the tape to the roller.

Concluding, heat losses to the environment are negligible for practical purposes in laser-assisted tape placement, until internal temperature gradients have decayed.

Later experiments will provide more proof of this assumption (Figure 5.8, Figure 5.10).

Heat flow 8. After the tape and substrate got into contact, the two bodies exchange heat. Later analysis will show how this can influence the cooling rate of the bond interface. This *inter-body* heat flow can be considered by numerical solutions and by approximated analytical solutions (Subsection 4.3.5). If the temperature profile within the tape is equal to that within the substrate, the inter-body heat flow can be neglected, because the (isolated) surface cooling of tape and substrate becomes symmetrical (please compare Figure 5.3, p. 74).

Thermal aspect 1. When the tape and the substrate get into contact at the nip point, a thermal resistance R_C occurs between the two bodies, but rapidly vanishes – assuming intimate surface contact takes place. Furthermore, the cooling behavior of the bond interface is mostly symmetrical during the intimate contact development, as the tape and substrate are generally heated up to similar temperature levels (Figure 5.2, p. 74). R_C has been neglected by all known authors so far and will so in this thesis.

Thermal aspect 5 and 6. At the micro level of a composite, the transient heat transfer differs locally by the heat flows from fiber to matrix and vice versa. Furthermore, the fiber *distribution* along the thickness can vary, depending on the type and quality of the tape (compare Figure 18.1, Figure 18.2). Thermal properties, like conductivity, can therefore vary throughout the thickness. Consideration of the tape-specific fiber distributions rules out general analysis of the process, as tapes differ among manufactures and at different positions in a tape spool. The implementation of varying properties and consideration of heat flows at the micro level increase the modelling complexity significantly; the simulation time rises by several orders of magnitude.

GROVE assumed that the tape can be modelled as homogeneous [GROV88 p. 368] (Figure 21.1, p. 201). Most successive authors followed this assumption, as will this thesis. Three aspects speak for this:

- The scales of the micro heat flows in-between fibers are several orders of magnitudes smaller than the global heat flows of interest ($> 25 \mu\text{m}$).
- Improvements in the fiber distribution are in ongoing development.
- The assumption of homogeneity makes it possible to derive general knowledge.

The material properties of the tape along the thickness will therefore be modelled by the *rule of mixture* and will be assumed as constant through the thickness.

Thermal aspect 7. Temperature-dependent properties can influence the heating and cooling behavior of polymers. However, most temperature-dependent properties can be averaged for the respective heating range (between T_i and T_{max}), leading to accuracies high enough for practical purposes. Averaging the specific heat capacity c_p and thermal conductivity k_z has therefore been applied by most authors [GHAS91] [ESCH01, p. 81] [TIER03] [STEY13, p. 50] [STIM15, p. 61-63].

Thermal aspect 8. As the thermal penetration depth in the thickness direction δ_{therm} is comparably low ($< 1 \text{ mm}$) relative to the radius of the roller ($\approx 40 \text{ mm}$) and the curvature of the substrate – e.g. a pipe with a 50 mm radius – the influence of the curvature can be neglected in heat transfer analysis of tape placement. This is obvious and has therefore been neglected by all known authors. For deeper analysis on the heat transfer in curved geometries, the author refers to [BEJA03, p. 181].

Thermal aspect 10. During melting, the latent heat of fusion of the polymer acts as a heat sink, and during crystallization as a heat source (in semi-crystalline polymers) (Figure 19.1, p. 192). Nonetheless, in comparison to other heat transfer terms, these are very weak phenomena, why they were neglected by most authors.

Thermal aspect 11. This thesis assumes the substrate to be well consolidated, without significant inter-layer thermal resistances.

Thermal aspect 12. The focus of this thesis is the short-time heating and cooling behavior of a *non-preheated* tape and substrate, because this is the most challenging and most common condition. Therefore, the initial condition is defined as $T_i = T_0$ with T_0 being an ambient temperature of 20°C.

Thermal aspect 13. During a manufacturing cycle, the irradiation time of the tape can change, due to deviations of the process speed or motion singularities, like starts/stops or slowdowns of the manipulator at sharp edges. However, for the most part, the tape speed is kept constant by the motion control unit. Irradiation per time does not change throughout the manufacturing cycle. For thermal analysis, most authors have therefore assumed the irradiation time to be constant.

Thermal aspect 14 and 15. In general, the heat flux distribution can be non-homogeneous in the process zone, because the roller and the substrate geometry lead to reflection and reduced intensity on the target surface [GROV88] [KOEL08, p. 59] [STOK14] [WEIL16b]. This effect is specific for each placement system and depends on several parameters, like roller diameter, mold geometry, laser angle, tape infeed angle and the reflectance of the material. The general effect on the surface temperature is well documented in [STOK14, p. 113]. It was found that the final surface temperature at the nip point varies slightly, roughly $\pm 10\%$, compared to a uniform homogeneous irradiation (depending on the considered material reflectance model).

For analysis of changing through-thickness temperature distributions $T(z)$ at varying speeds v_p (Chapter 5), these effects will be neglected for the purpose of generalization. It can also be assumed that *changes of the thermal profile behave self-similar to changes of the process speed, regardless of the respective machine setup*. The assumption is supported by the proportionality of the thermal penetration depth δ_{therm} and laser irradiation time t_L , given as:

$$\delta_{therm}(t_L) \approx \sqrt{4\alpha t_L}; \quad t_L = x_L/v_p \quad (4.10)$$

with α being the thermal diffusivity of the material [BEJA03, p. 981] [FAGH10, p. 266] [BERG11, p. 314] [POPR05, p.313]. Therefore, the analysis of the through-thickness temperature at varying speeds will consider a *homogeneous* heat flux distribution.

Finally, in most diode-laser-based systems with collimated top-hat laser spots, the heat flux in the process zone is nearly homogeneous over the heating length, so direct transfer of results is feasible (compare Figure 2.2, Figure 2.15 and [STEY13, p. 49]).

Thermal aspect 16. Carbon fibers act as a strong absorber, which leads to surface absorption in the upmost layers (Figure 4.6, Figure 21.2, p. 202) [GROU12, p. 31] [STEY13, p. 50]. In the case of glass fiber tapes, additives are commonly used to blacken the polymer, which leads to surface absorption as well [STIM15, p. 61-63]. In most industrial applications, the laser penetration depth δ_L is therefore significantly smaller than the heat penetration depth: $\delta_L \ll \delta_{therm}$. Therefore, the thermal analysis in this thesis will assume a *surface* heat flux. Volumetric absorption is neglected.

4.3.2 Description of the Simplified Model

Beschreibung des vereinfachten Modells

The thermal problem of laser-assisted tape placement was thoroughly reduced to its predominant heat transfer phenomenon – *conduction* – and its most relevant domain – the *through-thickness direction*. This is beneficial in the context of this thesis, as the through-thickness direction will be the main research subject in the coming sections.

The simplifications yield to the subsequent parabolic differential equation:

$$\frac{d^2T}{dz^2} = \frac{1}{\alpha} \cdot \frac{dT}{dt}; \quad \alpha = \frac{k_z}{\rho c_p} \quad (4.11)$$

with $T_i = T_0$ ($\approx 20^\circ\text{C}$) as initial condition, and

$$-k_z \frac{dT}{dz} \Big|_{z=0} = \dot{q}_0; \quad \frac{dT}{dz} \Big|_{z=d} = 0 \quad (4.12)$$

as boundary conditions. The surface heat flux $\dot{q}_0$ depends on the laser intensity I_L by $\dot{q}_0 = I_L \cdot a$, with a being the absorption coefficient. In this thesis, a is assumed as 1. The same assumption has been made by STEYER. Other authors have shown that the absorption coefficient can be < 1 [STOK14] and decreases with higher laser incidence angles. However, for the *purpose* of later analyses – *effect of increased process speed on $T(z)$* – optical phenomena are assumed constant and therefore not modelled.

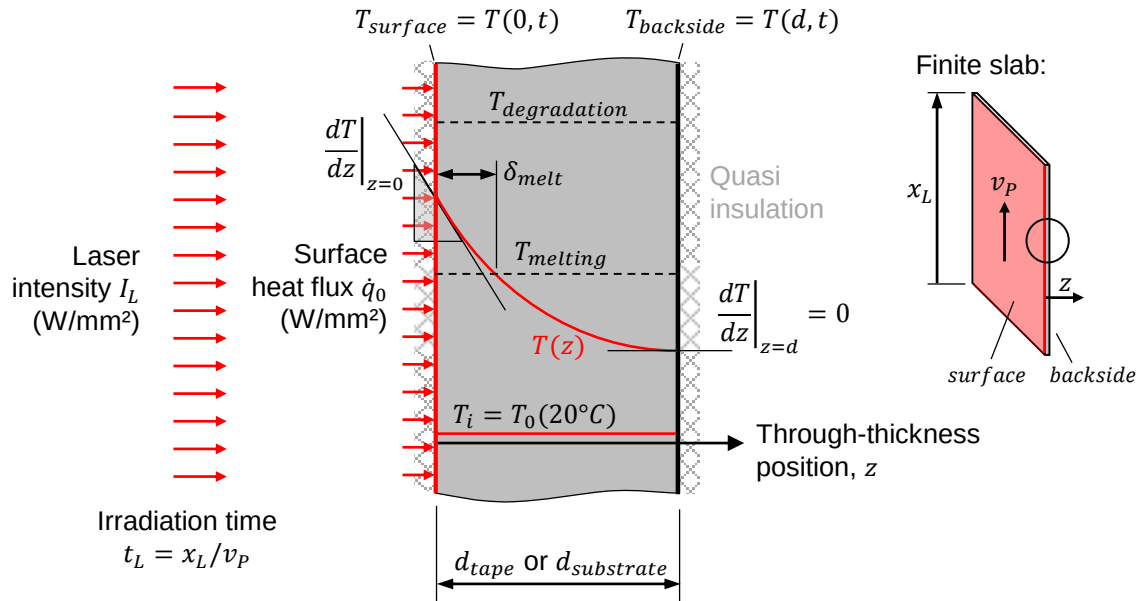


Figure 4.8: Finite slab model for analysis of the effect of process speed on the through-thickness temperature distribution in laser-assisted tape placement

Plattenmodell zur Einflussanalyse der Prozessgeschwindigkeit auf die Temperaturverteilung in Dickenrichtung beim lasergestützten Tapelegen

The idealized thermal body is quasi-insulated at the front and backside, so heat accumulation is modelled. This boundary condition was derived in Section 4.1. At the considered scales, the heat does flow orders of magnitude easier inside the tape, than to leave it to the surrounding air, roller or mold (Figure 4.6 and Figure 4.7).

4.3.3 Analytical Solutions

Analytische Lösungen

In Subsection 4.3.1 it was already derived that *heat accumulation* is a common effect in laser-assisted tape placement. It affects the analytical solutions insofar, as a distinction has to be made between processes where heat does reach the back of the body – termed *finite problem* –, and processes where heat does not reach the back – *semi-infinite problem*. This distinction is common in heat transfer analysis and can be made by use of the Fourier Number Fo (Section 5.2 will consider this subject in detail).

For now, it is important to keep in mind that *three* cases have to be differentiated:

Table 4.2: Overview of possible heating cases in laser-assisted tape placement

Übersicht der möglichen Erwärmungsfälle beim lasergestützten Tapelegen

	Tape	Substrate	Description
Case A	Finite	Finite	Both bodies accumulate heat
Case B	Finite	Semi-infinite	Only tape accumulates heat
Case C	Semi-infinite	Semi-infinite	No body accumulates heat

Finite : $Fo > 0.2$; Semi-infinite : $Fo < 0.2$, (compare Figure 5.7, p. 80)

Later thermal analysis will consider examples of “Case B” and “Case C” (Figure 5.2, p. 74). Those were found to be most common in laser-assisted tape placement. A hypothetical “Case D”, where the substrate accumulates heat and the tape does not, can occur in principle, but for this to happen the substrate must be thinner (or more conductive) than the tape, which is commonly not the case in tape placement.

4.3.4 Heating Process

Erwärmungsprozess

Semi-Infinite Problem. If heat does not reach back of the substrate (or tape), the problem can be described as *semi-infinite*. Solutions for Equation 4.11 of the semi-infinite problem are known in the advanced literature of mass and heat transfer and are presented in [BEJA03, p. 232-233] [POPR05, p. 51] [BERG11, p. 313]. For the internal temperature development over time, the following equation applies:

$$T(z, t_L) = T_0 + \frac{2 \cdot \dot{q}_0}{k_z} \cdot \sqrt{\alpha} \sqrt{t_L} \cdot ierfc\left(\frac{z}{\sqrt{4\alpha t_L}}\right); \quad \dot{q}_0 = \frac{P_L}{A_L} \quad (4.13)$$

with P_L as laser power, A_L as the irradiated surface, and

$$ierfc(A) = \frac{1}{\sqrt{\pi}} e^{-X^2} - X \cdot erfc(X) \quad (4.14)$$

Tables for $erfc(X)$ are given in the previously mentioned literature. For the determination of the *surface temperature* ($z = 0$), the term $ierfc(0) = 1/\sqrt{\pi} \approx 0.564$, yielding to:

$$T_{surface}(t_L) = T_0 + \frac{2 \cdot \dot{q}_0}{k_z} \cdot \sqrt{\alpha} \sqrt{t_L} \cdot \frac{1}{\sqrt{\pi}} \quad (4.15)$$

Similar solutions have been proposed for analysis of laser-assisted tape placement to describe the heating process within a tape – initially by VOR DEM ESCHÉ [ESCH01, p. 80] and later by others [STEY13, p. 50] [STIM15, p. 61-63].

Finite Problem. However, as shown in Section 4.1, the effect of heat accumulation cannot be neglected in tapes, because the internal thermal resistance by conduction R_{cond} is several orders smaller than the thermal resistance to the environment $R_{conv/rad}$ or to a solid (roller R_{roller} or mold R_{mold}). Therefore, the author proposes the use of alternative solutions for the tape:

A mathematical solution for the heat transfer problem of *finite* bodies was presented in [FAGH10, p. 255-259]. The non-homogeneous problem described by Equation 4.11 does not have a steady-state solution. Therefore, the method *variation of parameters* of MYERS (1987) was used to derive the following solution:

$$T(z, t_L, d) = T_0 + \frac{\dot{q}_0 \cdot d}{k_z} \cdot \left(Fo + \frac{(z/d)^2}{2} - z/d + \frac{1}{3} - \frac{2}{\pi^2} \cdot \sum_{n=1}^{\infty} \frac{\cos(n\pi(z/d)^2)}{n^2} e^{-(n\pi)^2 Fo} \right) \quad (4.16)$$

The equation is valid under the boundary conditions $0.2 < Fo < \infty$ and $0 < z < d$, so only for large Fourier numbers > 0.2 , which is the case for finite heating processes:

$$Fo = \frac{\text{heat diffusion rate}}{\text{heat storage rate}} = \frac{k_z}{\rho \cdot c_p} \cdot \frac{t_L}{d^2} = \alpha \cdot \frac{t_L}{d^2} \quad (4.17)$$

By comparison, the previously mentioned solution for *semi-infinite* bodies, Equation 4.13, is only valid for $0 < Fo < 0.2$ – when heat does not reach the back.

Equation 4.16 describes the temperature as a function of laser heating time t_L and position within the body in the through-thickness direction z . The laser heating time t_L is included in the Fourier number Fo .

The surface temperature can again be derived by setting $z = 0$ and yields to:

$$T_{surface}(t_L) = T_0 + \frac{\dot{q}_0 \cdot d}{k_z} \cdot \left(Fo + \frac{1}{3} - \frac{2}{\pi^2} \cdot \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-(n\pi)^2 Fo} \right) \quad (4.18)$$

Finite and Semi-Infinite Problem. As an alternative to the presented derivations, the *Method of Mirroring Heat Sources* can be used, to obtain *one* solution for *both* finite and semi-infinite bodies (translated from German: “*Methode der Spiegelquellen*”) [POPR05, p. 56].

It uses the feature that the heat is *quasi reflected* from the backside of the body, due to the high thermal resistances, therefore leading to “virtual” heat source terms at the backside and front side (compare Figure 4.6 and Figure 4.7). For deeper explanation of the method, the author refers to a visualization in the Appendix, Figure 13.1, p. 173).

Applying the Method of Mirroring Heat Sources can be written as a series, yielding to:

$$T(z, d, t_L) = T_0 + \frac{2 \cdot \dot{q}_0}{k_z} \cdot \sqrt{\alpha} \sqrt{t_L} \cdot \sum_{i=0}^{\infty} \left[ierfc \left(\frac{2d \cdot i + z}{\sqrt{4\alpha t_L}} \right) + ierfc \left(\frac{2d \cdot (i+1) - z}{\sqrt{4\alpha t_L}} \right) \right] \quad (4.19)$$

Using enough series, the equation generates equal results to Equation 4.16 and Equation 4.19. However, the advantage of Equation 4.19 is its limitless validity in the boundary conditions: $0 < Fo < \infty$ and $0 < z < d$.

Figure 4.9 (next page, right-hand side), shows the thermal penetration during a conventional heating process of a PEEK/CF tape of 0.15 mm thickness in comparison to a PEEK/CF substrate of 1 mm. The magnitude of surface heat flux $\dot{q}_0$ is chosen to achieve a final surface temperature of 410°C after 0.154 s for both tape and substrate. The exemplary process speed is 260 mm/s.

In the case of the thin tape, heat significantly accumulates during heating, whereas in the case of the thicker substrate it can penetrate deeper inwards. The substrate soaks up more heat than the tape, which is why the heating the tape requires less power – at least at low process speeds as will be seen later (Figure 5.2, p. 74). The example already shows the significantly different heating characteristic between *finite* and *semi-infinite* cases in laser-assisted tape placement. It should be noted again that both tape and substrate can be finite or semi-infinite, depending on the process and material parameters. Later analysis in Section 5.2 will *generalize* this correlation.

Laser Power and Heating Length. The respective *laser power* can be calculated by multiplying the surface heat flux with the heating length and the respective tape width: $P_L = \dot{q}_0 x_L w_{tape}$. A typical heating length in laser-assisted tape placement systems was found to be 40 mm [KOEL08, p. 32-40] [STEY13, p. 49] [MODI13, p. 2]. This heating length will be used in most following transient heat transfer analyses. For the case of a 25 mm-wide tape, the laser power P_L is 680 W for the tape and 1 kW for the substrate.

Equation 4.16 and Equation 4.19 can be used to derive temperature changes at certain positions in the time domain, by setting $z = 0$ for the *surface* temperature, $z = d$ for the *backside* (and if required, $z = d/2$ for the temperature at the *center* of the body).

Lumped Capacitance Method. At very low process speeds, when the temperature gradients are very flat, the temperature rises almost homogeneously within a finite tape or substrate. In this case, the heating of the body can be described by the *Lumped Capacitance Method*:

$$T_{hom}(t_L) = \dot{q}_0 A_L \cdot \frac{t_L}{\rho c_p \cdot A_L \cdot d} + T_i; \quad A_L = 1 \text{ mm}^2; \quad T_i = 20^\circ\text{C} \quad (4.20)$$

Especially for very thin tapes < 0.1 mm and slow processes, this method can be applied with reasonable errors. In general, it was found that for *Fourier numbers* of > 6.5 , the prediction accuracy of the surface temperature is $> 95\%$. In the Figure 5.7, p. 80, this limit case is depicted for various body thicknesses d and process speeds v_p (inversely proportional to irradiation times t_L).

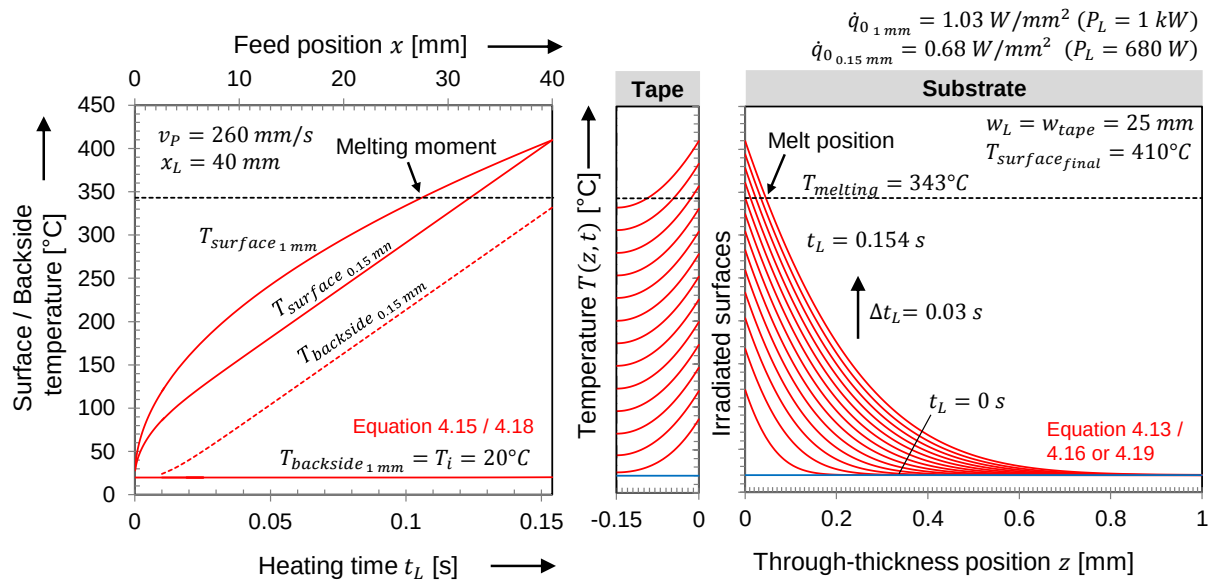


Figure 4.9: Result of the analytical solutions for a 0.15 mm-thick tape and 1 mm-thick substrate during *heating* in the time domain (left) and in the through-thickness direction (right). Material: PEEK/CF (parameters documented in Section 18.1)

Ergebnis der analytischen Lösung für ein 0,15 mm dickes Tape und ein 1 mm dickes Substrat während der Erwärmung im Zeitbereich (links) und in Dickenrichtung (rechts)

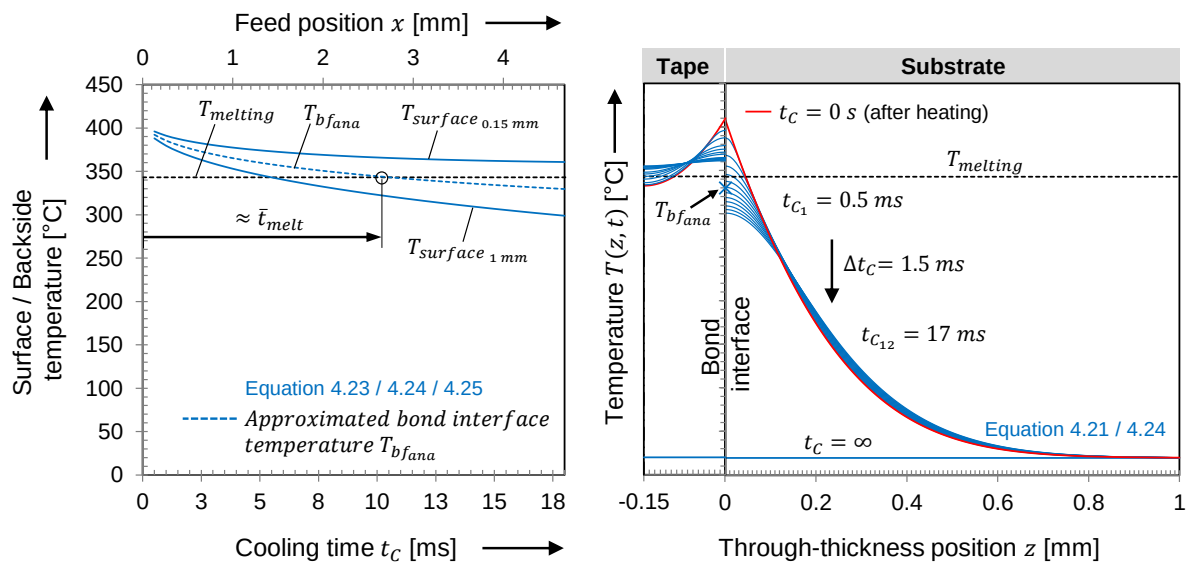


Figure 4.10: Result of the analytical solutions for a 0.15 mm-thick tape and 1 mm-thick substrate during *cooling* in the time domain (left) and in the through-thickness direction (right). Heat flow between tape and substrate after contact is approximated by the averaged surface temperature of tape and substrate

Ergebnis der analytischen Lösung für ein 0,15 mm dickes Tape und ein 1 mm dickes Substrat während der Abkühlung im Zeitbereich (links) und in Dickenrichtung (rechts). Wärmefluss zwischen Tape und Substrat nach dem Kontakt ist genähert als gemittelte Oberflächentemperatur von Tape und Substrate

4.3.5 Cooling Process

Abkühlprozess

Previous sections confirmed the assumption that the dominant heat transfer mechanism during *heating* is *through-thickness conduction*. Section 4.1 reinforced this assumption by analysis of a thermal resistances network model (Figure 4.6). In this thesis, it is further proposed that the through-thickness conduction is also the dominant heat transfer mechanism during the *cooling phase* – especially at higher process speeds, with consequent steeper temperature gradients (see forward to Figure 5.2).

The difference, compared to the heating phase, is that during the cooling phase tape and substrate are not isolated anymore and can exchange heat over the bond interface from one body to the other. This heat flow $\dot{Q}_C$ becomes most relevant when the tape and substrate are heated very *asymmetrically*. In order to analyze the cooling process with high precision, numerical solutions are therefore the most-appropriate method and will be utilized in Section 4.2, e.g. Figure 5.5, p. 78.

Nonetheless, it is still possible to utilize analytical solutions for approximations, by making feasible assumptions. But first, two analytical solutions will be presented for the case of *isolated* tape and substrate:

Semi-Infinite Problem. Similar to the heating processes, cooling processes have to be distinguished whether heat (significantly) reaches the back of the body during cooling or not. For semi-infinite problems, mathematical solutions have been presented in [POPR05, p. 51]. The solution of Equation 4.11 yields to:

$$T(z, t_L, t_P) = T_0 + \frac{2 \cdot \dot{q}_0}{k_z} \cdot \sqrt{\alpha} \left[\operatorname{ierfc} \left(\frac{z}{2\sqrt{\alpha t_P}} \right) \sqrt{t_P} - \operatorname{ierfc} \left(\frac{z}{2\sqrt{\alpha(t_P - t_L)}} \right) \sqrt{(t_P - t_L)} \right] \quad (4.21)$$

with t_L being the laser heating period and t_P being the overall considered time. The cooling time t_C can be obtained by:

$$t_C = t_P - t_L \quad (4.22)$$

By setting $z = 0$ we obtain a solution for the surface temperature during cooling:

$$T_{\text{surface}}(t_L, t_P) = T_0 + \frac{2 \cdot \dot{q}_0}{k_z} \cdot \frac{1}{\sqrt{\pi}} \sqrt{\alpha} \cdot (\sqrt{t_P} - \sqrt{(t_P - t_L)}) \quad (4.23)$$

It is important to note that these solutions do not consider the heat accumulation effect, prior – or after – cooling. They are therefore only valid under the following conditions: $0 < Fo < 0.2$ and $0 < z < \infty$.

Finite and Semi-Infinite Problem. In the literature, no analytical solution for the transient temperature distribution $T(z, t)$ during cooling of a *finite* case was identified. Therefore, the *Method of Mirroring Sources* was utilized to achieve such a solution. Applying the method to Equation 4.21 – analogous to the heating equations – yields to Equation 4.24 on the next page, written as a series.

A principle result is shown in Figure 4.10 (right-hand side, 0.15 mm-thick tape). Further results will be shown later in Figure 5.3, p 74 (left-hand side, 0.25 mm-thick tape).

$$\begin{aligned}
T(z, d, t_L, t_P) = T_0 + \frac{2 \cdot \dot{q}_0}{k_z} \sqrt{\alpha} \\
\cdot \left[\sqrt{t_P} \cdot \sum_{i=0}^{\infty} \left(\operatorname{ierfc} \left(\frac{2d \cdot i + z}{\sqrt{4\alpha t_P}} \right) + \operatorname{ierfc} \left(\frac{2d \cdot (i+1) - z}{\sqrt{4\alpha t_P}} \right) \right) \right. \\
\left. - \sqrt{t_P - t_L} \right. \\
\left. \cdot \sum_{i=0}^{\infty} \left(\operatorname{ierfc} \left(\frac{2d \cdot i + z}{\sqrt{4\alpha(t_P - t_L)}} \right) + \operatorname{ierfc} \left(\frac{2d \cdot (i+1) - z}{\sqrt{4\alpha(t_P - t_L)}} \right) \right) \right]
\end{aligned} \quad (4.24)$$

The solution was found to apply for the boundary conditions: $0 < Fo < \infty$; $0 < z < d$. Its validity was proven by comparisons to numerical solutions and by experiments on heating and subsequent cooling of tapes in ambient air (see Figure 5.8, Figure 5.10, p. 83, 86).

Time Domain. The *surface* and *backside* temperature can be obtained by setting the position parameter z to either 0 or d , analogous to the heating problem (Figure 4.10). It can be observed that the substrate surface – left isolated – exhibits a stronger cooling rate, because the heat can penetrate the thicker body more easily, whereas the heat-soaked tape cannot lose the heat by conduction in a similar way. It has to be noted that this holds true for the *short-time domain* of the cooling process. Over the long-term domain ($\gg 100$ ms), when tape and substrate approach *equilibrium*, both tape and substrate will lose relatively more heat to the environment by convection/radiation as well as to the mold (compare Figure 5.10, p. 86). *In the short-time domain of cooling however, the temperature gradients and through-thickness conduction dominate.*

Bond Interface Temperature Approximation. Equation 4.21 and 4.24 are fully valid to predict the *isolated* cooling of the bodies (tape/substrate). In tape placement however, the tape and the substrate are in contact with each other during cooling.

Notwithstanding the above, according to GROUVE, the bond interface temperature T_{bf} at the nip point can be approximated by averaging the final surface temperatures of tape and substrate [GROU12, p. 89], from [BERG11, p. 315]. It is proposed to *extend* this assumption for the short-time cooling period. This is feasible when: (a) Significant thermal gradients occur, which is generally the case in laser-assisted tape placement at speeds > 200 mm/s and (b) the considered cooling time t_c is moderate, because the prediction error increases with the cooling time. The solution is then obtained by averaging either Equation 4.21 or 4.24, depending cases presented in Table 4.2:

$$T_{bfana}(t_c) \approx \frac{T_{surface_{tape}}(t_c) + T_{surface_{substrate}}(t_c)}{2} \quad (4.25)$$

A result of the approximation is plotted in Figure 4.10, left-hand side (in the time domain). The resulting approximate melt dwell time $\bar{t}_{melt}$ is depicted at the intersection between $T_{bfana}(t)$ and $T_{melting}$. Figure 5.3 shows further use of the approximation in the through-thickness domain, marked by the crosses at the bond interface position.

4.4 Qualification by Comparisons between Model Complexities

Qualifizierung durch Vergleiche verschiedener Modellkomplexitäten

Before the models were used for process analysis, a comparative investigation was performed to assess the differences among the model predictions. Two numerical simulations were conducted: one with the simplified model (Figure 4.8, p. 60) and one with the detailed model (Chapter 4.2). The result of the detailed model is used as a *reference*, because it includes most known thermal aspects and heat flows (Table 4.3).

Reference Case. For the reference case, the process parameters $\dot{q}_{0\text{ tape}}$, $\dot{q}_{0\text{ substrate}}$ and t_L were set in such a way that the tape and substrate both reach $410^\circ\text{C} \pm 1^\circ\text{C}$ after heating. The parameters were then applied to solve the simplified model (analytical/numerical). The cooling period t_C was chosen to enable a cooling of the bond interface until the melting temperature T_{melting} (343°C) is reached (≈ 30 ms).

Table 4.3: Overview of the modelled thermal aspects for the model comparison

Übersicht der modellierten thermischen Aspekte zum Modellvergleich

No. Heat flows	Model:	Detailed	Simplified	
	Solution:	1) Numerical	2) Numerical	3) Analytical
1 Surface heat flux by laser irradiation		x	x	x
2 Conduction in width direction		/	/	/
3 Conduction in fiber direction		/	/	/
4 Conduction in thickness direction		x	x	x
5 Convection and radiation		x	/	/
6 Heat flow to the roller		x	/	/
7 Heat flow to the mold		x	/	/
8 Heat flow between tape and substrate		x	x	/
No. Thermal aspects				
1 Thermal resistance from tape to substrate		x	/	/
2 Speed-dependent convection coefficient		x	/	/
3 Temperature-dependent radiation coefficient		x	/	/
4 Anisotropic material conductivity		x	/	/
5 Fiber-matrix micro heat flow		/	/	/
6 Material inhomogeneity at the micro level		/	/	/
7 Temperature-dependent material properties		x	/	/
8 Curvature of tape and substrate		/	/	/
9 Heat accumulation		x	x	x
10 Latent heat of fusion and crystallization		x	/	/
11 Inter-layer contact resistance		/	/	/
12 Pre-heated substrate		/	/	/
13 Changing irradiation times		/	/	/
(Optic-related) thermal aspects				
14 Non-homogenous heat flux distribution		/	/	/
15 Shading area		/	/	/
16 Volume absorption		/	/	/

Finite VS. Semi-Infinite. The investigations were purposefully conducted for (1) a *finite* case, where heat does reach the back of the body – a 0.25 mm-thick tape –, and (2) for a *semi-infinite* case, where heat does *not* reach the back – 1 mm-thick substrate. The respective configuration was determined iteratively.

Material Data. PEEK/CF was chosen as material, because it offers the best available data in the literature. The temperature-dependent material properties were taken from COGSWELL (Appendix, Section 18.1) [COGS92, p. 241]. The latent heat of fusion and crystallization heat sinks / heat sources were modelled according to values taken from VOR DEM ESCHÉ and GAO & Kim (Appendix, Figure 19.1, p. 192) [GAO00a, p. 521] [ESCH01, p. 67-68]. For the simplified model, the material properties were averaged over the temperature range from 20°C and 425°C, which is roughly the range the material undergoes during heating ($T_{surface_{final}} = 410^\circ\text{C}$).

Roller Boundary Condition. The detailed model assumes the tape to be in contact with a metallic roller of 20°C (with infinite conductivity) at a high heat transfer coefficient h_{roller} of 400 W(m²·K) throughout the entire heating and cooling cycle, as a worst-case assumption, to evaluate the impact of this boundary condition.

Quantitative Measure. To gain a quantitative measure of how the models agree, the following equation was used:

$$Agreement = \frac{T_{surface_{cplx}} - T_i}{T_{surface_{spld}} - T_i} \cdot 100 [\%]; \quad T_i = 20^\circ\text{C} \quad (4.26)$$

where $T_{surface_{cplx}}$ is the final surface temperature of the detailed model (numerically solved) and $T_{surface_{spld}}$ the final surface temperature of the simplified model (numerically and analytically solved). The results are summarized in Table 4.4 and Figure 4.11.

Observations. It can be observed that the detailed model predicts the lowest temperature distribution *level* $T(z)$ after heating, for both the tape as well as the substrate (red graphs). The same holds true for the curves after cooling (blue graphs). During heating, all temperature distributions are *proportional* along the through-thickness position z for both numerical (simplified/detailed) and analytical solutions.

The maximum *prediction error* of the surface temperature after heating is < 10%. The deviation can mainly be ascribed to the non-linear temperature-dependent material properties, $c_p(T)$ and $k_z(T)$, which are averaged for the case of the simplified model. Additional *parameter variation analyses* showed that the temperature level is sensitive to changes of the *averaging range* – however its overall significance remained comparably low (< 10 %) for the investigation of varying process speeds.

Another overestimated parameter appears to be the boundary condition at the backside (roller/mold). The roller was found to act as a rather *weak heat sink*. It only slightly limits the backside to heat up in the same way as if a roller was not considered (observe the slight deviation in the shape of the temperature curves at the backside.) The general difference of the temperature level within the tape is much more sensitive to the averaging range of the heat capacity $\bar{c}_p$. If the roller contact is modelled only during its short contact with the tape (Figure 4.3), this difference at the backside is even smaller. The deviation does also shrink further with higher process speeds, as the roller contact time decreases and the tape backside remains colder (Figure 5.2).

All models and solutions predict the heat accumulation effect in the tape. Due to the effect, the tape requires 25% less surface heat flux $\dot{q}_0$ ($\sim$ laser power P_L) than the substrate to reach the defined surface temperature of 410°C (at 260 mm/s). Please note that in conventional systems the laser angle α_L is the control value, not P_L .

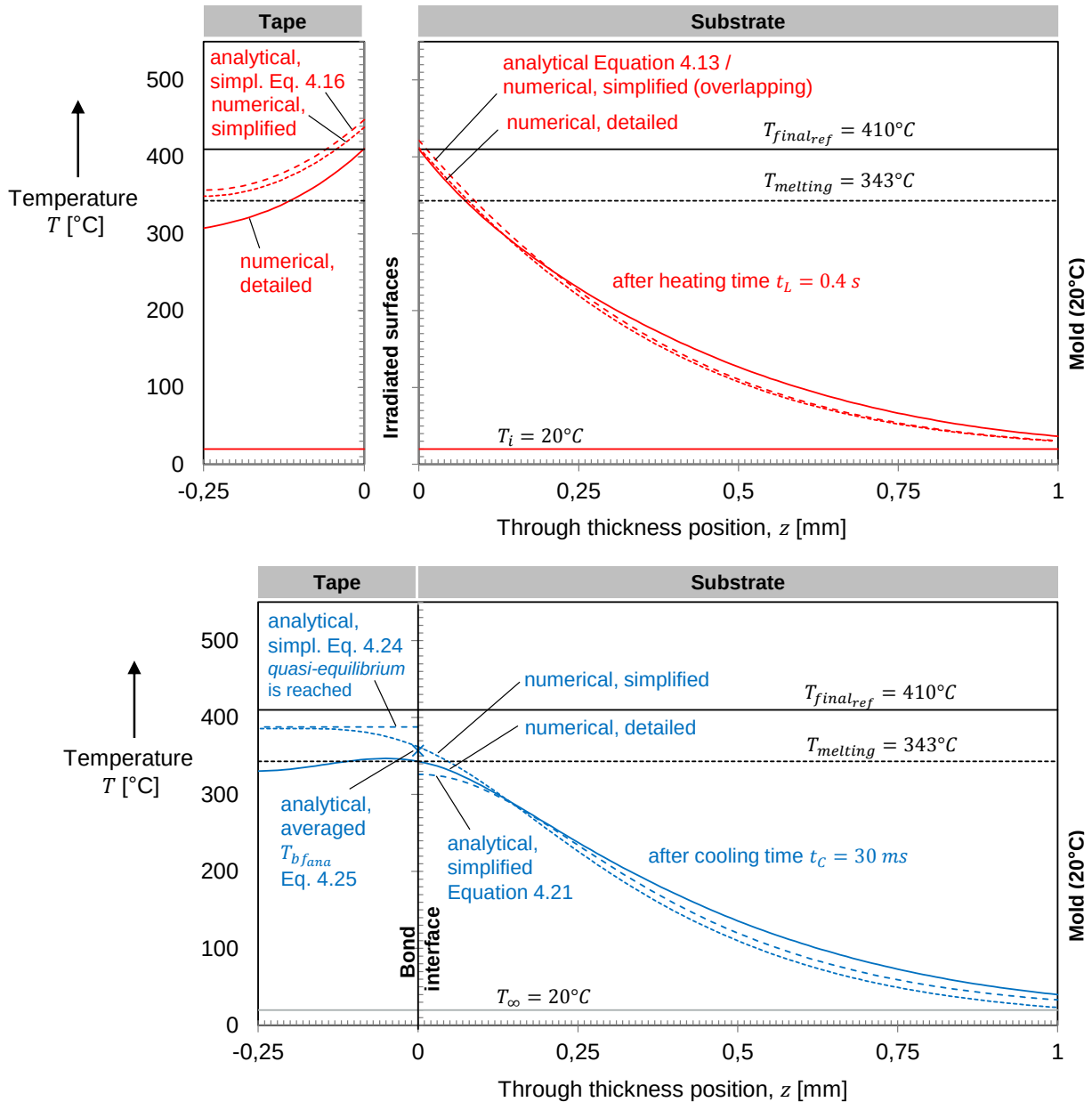


Figure 4.11: Comparison between numerical and analytical calculation as well as detailed and simplified model after heating (top) and after 30 ms cooling (bottom)

Vergleich von numerischer und analytischer Rechnungen sowie detailliertem und vereinfachtem Modell nach Erwärmung (oben) und Abkühlung (unten)

The longer the cooling time t_C , the higher the deviation between analytical and numerical solution will become, because the analytical solution considers the inter-body heat transfer only by averaging the surface temperatures of an isolated tape and substrate (Equation 4.25). Nonetheless, the deviation will only become significant long after the bond interface temperature decreased below the melting temperature. The maximum deviation after cooling in the bond interface was found to be 6%.

Even the worst-case scenario of a metallic roller (at 20°C) in contact over the entire process and a relatively high heat transfer coefficient of 400 W/(m²·K) did not change this condition very much. Later analyses found that with higher process speeds v_p and shorter heat transfer periods, this assumption becomes even more true, as the surrounding heat losses (by roller/convection/radiation) further decrease, while the surface heat flux, induced by the laser, remains (Figure 5.2, Figure 5.3). In such conditions, steep gradients occur, preventing heat to reach the backside anyway.

Table 4.4: Result of the comparison between models and solution methods

Ergebnis des Vergleichs zwischen Modellen- und Lösungsmethoden

	Model:	Detailed (ref.)	Simplified	
	Solution:	1) Numerical	2) Numerical	3) Analytical
Results		Tape		
$T_{surface}$ after heating / Agreement		410°C / 100%	438°C / 93%	448°C / 91%
$T_{surface}$ after cooling / Agreement		343°C / 100%	362°C / 94%	357°C / 96%
Computation time		3 min./curve	10 sec./curve	- /all curves
		Substrate		
$T_{surface}$ after heating / Agreement		410°C / 100%	421°C / 97%	422°C / 97%
$T_{surface}$ after cooling / Agreement		343°C / 100%	364°C / 94%	362°C / 94%
Computation time		4 min./curve	11 sec./curve	- /all curves

Interim Conclusion. In view of tolerances in the system and material property data, the simplified model seems to be a very feasible and efficient tool for analysis of laser-assisted thermoplastic tape placement. Model restrictions have to be kept in mind – e.g. that inter-layer contact resistances are not modelled. The often-made assumption that through-thickness conduction is the most significant mode of heat transfer in laser-assisted tape placement can be confirmed. Convection, radiation and the heat transfer to the external solids, like roller or mold, do influence the results by < 10% in the (most relevant) short-time domain. Consideration of the roller as a heat sink is expected to be overestimated in the literature, especially for the case of high-speed processes.

Notice however that a *long-term preheating* of the substrate by the use of a warm-temperate mold does still influence the through-thickness temperature distribution, because during a whole manufacturing process, the heat has enough time to transfer from the mold surface into the workpiece, and diffuse. In such a condition the initial substrate temperature equals not T_0 but that of the mold: $T_{i_substrate} = T_{mold}$. Previous authors used temperatures between 25-210°C [KERM15, p.82].

The most significant boundary conditions were found to be the *surface heat flux* $\dot{q}_0$ and *irradiation time* t_L with a prediction accuracy of > 90% (at > 260 mm/s). The prediction accuracy only increases with higher speeds. An experimental validation will be presented in Sections 5.2, in the context of varying process speeds. The presented equations can possibly also be used to predict and analyze the infrared heating of thermoplastic composite sheets („organo sheets“).

5 Investigations on the Effect of Process Speed on the Through-Thickness Temperature Distribution

Untersuchungen zur Wirkung der Prozessgeschwindigkeit auf die Temperaturverteilung in Dickenrichtung

State-of-the-art lasers provide powers of $\gg 10$ kW [LASE13a]; significantly more than the implemented lasers in today's placement machines. Tailored optics have become widely available, which can shape the laser beam, customized for the process requirements [LASE13b] [LASE13c]. In addition, fast electronics and contact-free pyrometers enable closed-loop (surface) temperature controls with high accuracies, to keep the desired surface temperature within a tolerable process window [BREC16].

Considering these technological boundary conditions raises the question whether laser-assisted tape placement is limited in terms of process speeds at all. The question to answer is: What exactly happens *thermally* at higher speeds, when the laser power is not restricted and the surface temperature well controlled? How does the process speed exactly affect the temperature distribution in the through-thickness direction and consequently the melt pool depth, dwell time and cooling dynamics?

5.1 Temperature Gradients at Increased Process Speeds and their Decay during Cooling

Temperaturgradienten bei steigenden Prozessgeschwindigkeiten und deren Abklingverhalten bei der Abkühlung

5.1.1 Investigation by Use of Simplified Model and Analytical Solutions

Untersuchung mittels vereinfachten Modells und analytischer Lösung

This subsection will make use of the analytical solutions presented in Subsection 4.3.4-4.3.5. The equations make it possible to plot many curves at the same time without time delay to get a full picture of the spectrum of final temperature distributions. The section thereafter will use the detailed numerical model of Section 4.2 for comparisons.

We want to investigate what happens at higher process speeds, when the laser power is not limited. For this to observe, an additional equation is required, which sets the final surface temperature after heating as a *setpoint* value for all process speeds v_p of interest. *It is this boundary condition which emulates a high-power laser in combination with a well-functioning closed-loop control of the surface temperature* (Figure 2.2).

Equation 4.16 has to be converted to the surface heat flux $\dot{q}_0$ (Equation 5.1, next page). With this equation it becomes possible to determine the required surface heat fluxes and laser powers for a given final surface temperature and body thickness d at various process speeds (Figure 5.1). Note that different laser irradiation times t_L correlate with respective process speeds v_p , because $v_p = x_L/t_L$, and the laser power correlates with the surface heat flux by $P_L = \dot{q}_0 x_L w_{tape}$, assuming an absorption coefficient of 1.

$$\dot{q}_0(T_{surface_final}, t_L, d) = \frac{k_z (T_{surface_final} - T_0)}{d \left[Fo + \frac{1}{3} - \frac{2}{\pi^2} \cdot \sum_{n=1}^{\infty} \left(\frac{1}{n^2} e^{-(n\pi)^2 Fo} \right) \right]}; \quad Fo = \alpha \cdot \frac{t_L}{d^2} \quad (5.1)$$

By this rearrangement, the surface temperature $T_{surface}$ becomes the variable $T_{surface_final}$, rather than an outcome, and can be set flexibly. In the following analysis, the final surface temperature is set to the recommended processing temperature for PEEK/CF-tapes: 410°C. [LATR03, p. 9] [TENC17, p. 2]. The melting temperature is therefore exceeded by 60°C.

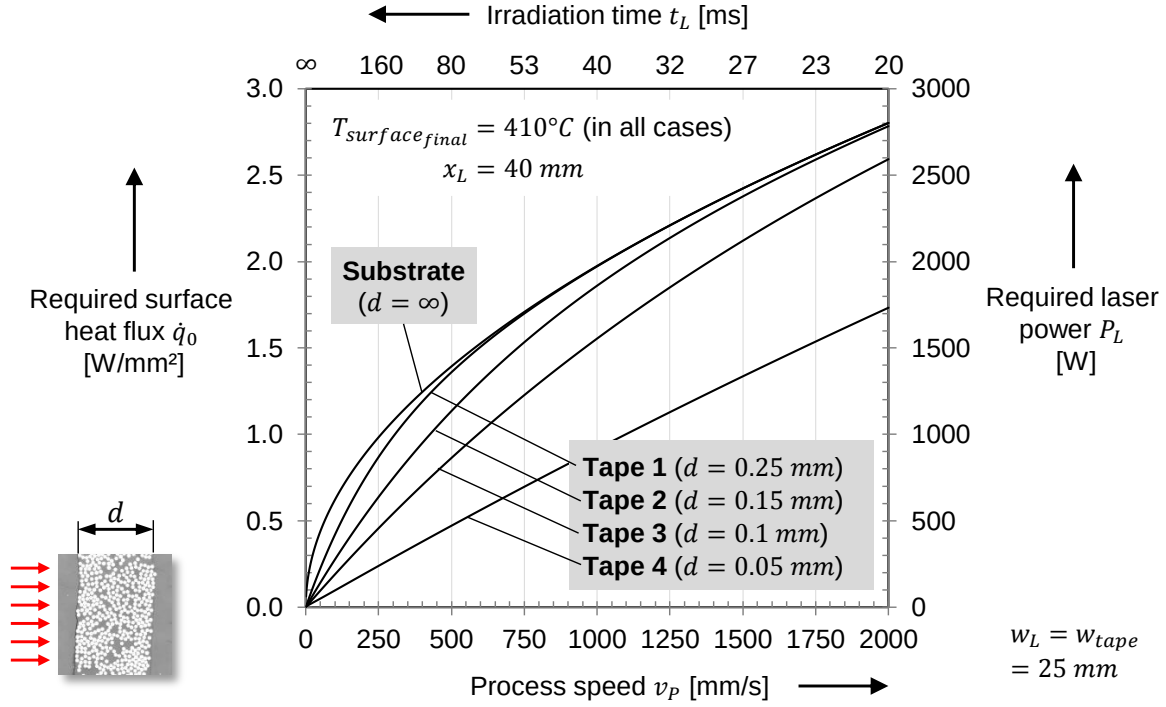


Figure 5.1: Required surface heat flux and respective laser power for tapes of various thickness and for a non-preheated semi-infinite substrate, to reach 410°C

Erforderliche Oberflächenwärmestromdichte und entsprechende Laserleistung für Tapes verschiedener Dicken und für ein unvorgewärmtes quasi-unendlich dickes Substrat, um 410°C zu erreichen

Observations. It can be observed that at lower speeds, the thinner tapes require much less laser power to reach 410°C. This can be attributed to the heat accumulation effect (Figure 4.9, Figure 5.2). At roughly 50 mm/s, the substrate requires twice as much power than the 0.25 mm-thick tape and 2.5-times as much power than the 0.15 mm-thick tape to reach 410°C.

With higher speeds however, all finite tapes become inevitably semi-infinite. At this point, all require equal laser powers to reach 410°C – the (nearly fixed) thermal diffusivity dominates the problem, rather than the heat accumulation effect. For the 0.25 mm-thick tape, the difference starts to become insignificant at ≈ 500 mm/s. A practically symmetrical heating (and cooling) of a 0.25 mm-thick tape and semi-infinite substrate requires therefore process speeds > 500 mm/s (Figure 5.2 and Figure 5.3). Symmetrical heating of a thick substrate and 0.15 mm-thick tape occurs much later.

The next analysis of the through-thickness temperature distribution $T(z)$ will make this symmetry clearer (see Figure 5.2). The curves in Figure 5.1 correspond with the observations made in Section 5.2. DI FRANCESCO et al. recently investigated the speed- and power-dependent nip point temperature [FRAN17, p. 412]. Their findings are in good agreement with the predictions made by the presented model.

Through-Thickness Analysis. With the results of Equation 5.1 and the equations from Section 4.3 it becomes possible to derive the final temperature distributions $T(z)$ at various process speeds, yet equal final surface temperature. Figure 5.2 shows the result for two typical bodies: a 0.25 mm-thick tape and a 1 mm-thick substrate.

Figure 5.3 shows the resulting cooling behavior of three distinct cases – $v_p = 55$ mm/s, 235 mm/s and 4000 mm/s –, by plotting the resulting temperature distribution after an exemplary cooling time t_c , according to Equation 4.21 and 4.24. A cooling time of 20 ms was chosen for demonstration purposes. The main process parameters and resulting thermal features are shown in the subsequent table:

Table 5.1: Parameters for the analytical investigation of changing temperature distributions at increasing process speeds and their decaying behavior

Parameter zur analytischen Untersuchung sich verändernder Temperaturverteilungen bei steigender Prozessgeschwindigkeit und deren Abklingverhalten

Cases	Lowest process speed		Common process speed		Highest process speed	
	Tape	Substrate	Tape	Substrate	Tape	Substrate
Process parameters						
Process speed v_p	55 mm/s		235 mm/s		4000 mm/s	
Required surface heat flux $\dot{q}_0$	0.25 W/mm ²	0.47 W/mm ²	0.86 W/mm ²	0.98 W/mm ²	4.04 W/mm ²	4.04 W/mm ²
Req. laser power P_L for tape width of 25 mm	250 W	470 W	860 W	980 kW	4.04 kW	4.04 kW
Irradiation time t_L	0.73 s		0.17 s		0.01 s	
Resulting features						
Melt pool depth δ_{melt} after heating	250 μ m	100 μ m	60 μ m	50 μ m	10 μ m	10 μ m
Bond interface temp. after cooling $T_{bf,ana}$	365°C		312°C		144°C	
Cooling rate $\Delta T_{bf}/\Delta t_c$	45°C in 20 ms		98°C in 20 ms		266°C in 20 ms	
Melt pool depth δ_{melt} after cooling	250 μ m	100 μ m	solidified	solidified	solidified	solidified
Energy input for 1 kg placed tape mass E_{1kg}	1334 kJ		798 kJ		206 kJ	

Surface temperature after heating = 410°C (in all cases)

Considered cooling time $t_c = 20$ ms; Heating length $x_L = 40$ mm

Intermediate process speeds can be calculated with the irradiation time steps $\Delta t_{Lstep} = 40$ ms

The plotted curves reveal the following general phenomenon: The thermal penetration δ_{therm} decreases with higher speeds, due to the decreasing time for thermal diffusion ($t_L \downarrow$, Eq. 4.10). With increasing process speed (and laser power), the temperature distribution shifts towards the surface. This effect has been forecasted by GROUVE and was termed as the development of a “[...] *distinct skin layer*” [GROU12, p. 135]. The phenomenon is comparable to a steak on an increasingly hot cooking plate.

Energy demand. The thermal energy for 1 kg placed tape can be obtained by:

$$E_{1kg} = (P_{L_{tape}} + P_{L_{substrate}}) \cdot m_{tape} / (d_{tape} w_{tape} v_P \rho); \quad m_{tape} = 1kg \quad (5.2)$$

Note that only the heated *tape* adds to the part's mass. The 55 mm/s process displays the highest heat soak; it requires therefore the most energy (Table 5.1).

Bond Interface. It can be noticed that: *the higher the process speed, the steeper the temperature gradient, the more rapidly the bond interface cools down*. This effect is root-caused by the higher thermal potential over a shorter distance (compare Equation 4.6, p. 54). Depending on the thermal diffusivity of the composite, the heating process tends towards steeper or flatter gradients.

Interim Conclusions. The analysis shows that in terms of available laser power on the market ($\gg 10$ kW), no technical restriction applies to laser-assisted tape placement. Even at uncommon process speeds of 4000 mm/s, the required overall laser power of 8 kW can be provided by the market (for 25 mm-wide tapes) and is sufficient to heat up high-temperature tapes, like PEEK/CF, 60°C above its melting temperature. However, it must be observed that the process speed also leads to significant *secondary phenomena* in the through-thickness direction z :

- *thinning* of the melt pool δ_{melt} , *shortening* of the melt dwell time t_{melt}
- *higher* bond interface cooling rates $\Delta T_{bf} / \Delta t_C$
- changing through-thickness *elastic modulus* (subject of Section 5.8)

The main cause for these phenomena is the shifting temperature gradient within the material. It is also important to notice that *the observed steepening of the temperature gradient (with higher process speeds) will occur irrespectively of the specific machine setup, the specific optical phenomena, material properties or degree of detail of the model*. Consequently, the heating of tapes via laser technology will always lead to a shifting temperature distribution towards the surface at increasing process speeds, *if no further measures on the laser irradiation distribution are taken*. The findings lead to the question of how critical the changes are for the bonding quality and how they can influence the consolidation process in general. This will be the topic in Chapter 6.

5.1.2 Investigation by Use of Detailed Model and Numerical Solution

Untersuchung mittels detailliertem Modell mit numerischer Lösung

Motivation. The advantage of the *detailed numerical* model is its ability to predict the bond interface temperature T_{bf} more accurately, by considering the inter-body heat flows among tape and substrate after contact. These heat flows were not possible to consider with the analytical solutions directly, why an approximation had to be made by averaging the surface temperatures of *isolated* tape and substrate (Equation 4.25).

Furthermore, additional thermal aspects can be considered by the detailed numerical model, like temperature-dependent non-linear material properties. The numerical model will therefore be used to *crosscheck* the results of the analytical results.

Parameter Determination. Solving the numerical model for a predefined final surface temperature is not as trivial as in the analytical method. An automatic finding of the parameters P_L and $\dot{q}_0$ would require a self-optimizing FE model. This was not realized in this thesis. Instead, the respective parameters were found by manual iterations (Table 5.2). The iterations were stopped after the parameter setting for a final surface temperature $410^\circ\text{C} \pm 1^\circ\text{C}$ was found.

Case Analysis. The effect of process speed is shown by analysis of two distinctive process speeds: 55 mm/s and 2000 mm/s. These values are chosen because they represent two ends of the spectrum of conventional process speeds in laser-assisted tape placement. The result of the through-thickness temperature development $T(z, t)$ is displayed in Figure 5.4 for the heating process and in Figure 5.5 for the follow-up cooling process. Again, in both cases the surface reached 410°C after heating.

Observations. Within the tape, it can be observed that the temperature develops *not* as *continuously* as in the analytical solution. For this to recognize, please compare the time steps Δt_L to Figure 4.9. The difference is caused by the temperature-dependent material properties, especially the specific heat capacity c_p , which increases with higher temperatures (Figure 19.1, p. 192). Nonetheless, both the analytical solution, with averaged material properties, and the numerical solution, with temperature-dependent properties, predict similar laser powers to reach 410°C . Optimization of the averaging range of $\bar{c}_p$ improves the analytical prediction.

Table 5.2: Parameters for the numerical investigation of changing temperature distributions at increasing speeds and their decaying behavior

Parameter zur numerischen Untersuchung sich verändernder Temperaturverteilungen bei steigender Prozessgeschwindigkeit und deren Abklingverhalten

Cases	Lowest considered process speed		Highest considered process speed	
	Tape	Substrate	Tape	Substrate
Process parameters				
Process speed v_p	55 mm/s		2000 mm/s	
Required surface heat flux $\dot{q}_0$	0.302 W/mm ²	0.46 W/mm ²	2.73 W/mm ²	2.73 W/mm ²
Laser power P_L for tape width of 25 mm	302 W	460 W	2.73 kW	2.73 kW
Irradiation time t_L	0.73 s		0.02 s	
Resulting features	Tape	Substrate	Tape	Substrate
Melt pool depth δ_{melt} after heating	200 μm	100 μm	16 μm	16 μm
Bond interface temp. after cooling T_{bfnum}	368 $^\circ\text{C}$		200 $^\circ\text{C}$	
Cooling rate $\Delta T_{bf}/\Delta t_c$	42 $^\circ\text{C}$ in 20 ms		210 $^\circ\text{C}$ in 20 ms	
Melt pool depth δ_{melt} after cooling	250 μm	100 μm	solidified	solidified
Energy input for 1 kg placed tape mass E_{1kg}	1412 kJ		278 kJ	

Surface temperature after heating = $410^\circ\text{C} \pm 1^\circ\text{C}$ (in both cases)

Considered cooling time $t_c = 20$ ms; Heating length $x_L = 40$ mm

The numerical solution confirms the observations made with the analytical analysis: a thinning of the melt pool δ_{melt} , decreasing melt dwell time t_{melt} and increasing cooling rates of the bond interface $\Delta T_{bf}/\Delta t_c$ (next page) at increasing process speeds v_p for a predefined final surface temperature $T_{surface\,final}$.

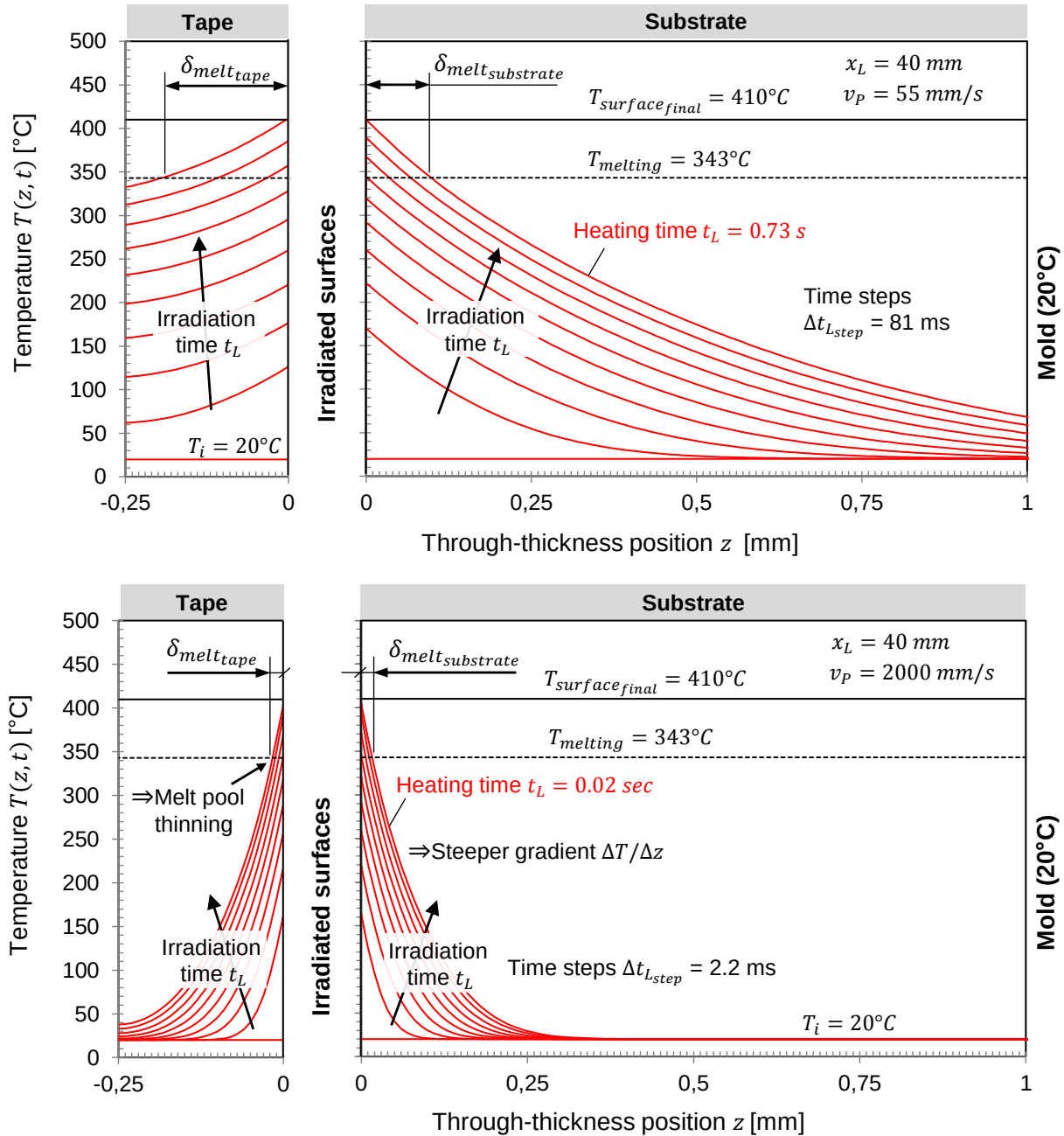


Figure 5.4: Time-dependent temperature development within a 0.25 mm-thick tape (left) and a 1 mm-thick substrate (right) for a relatively low process speed of 55 mm/s (top) and a relatively high process speed of 2000 mm/s (bottom); both processes reach an equal final surface temperature.

Zeitabhängige Temperaturentwicklung in einem 0,25 mm dicken Tape (links) und 1 mm dicken Substrate (rechts) für eine relative langsame Prozessgeschwindigkeit (oben) und relativ hohe Prozessgeschwindigkeit von 2000 mm/s (unten); beide Prozesse erreichen gleiche finale Oberflächentemperatur.

After contact of tape and substrate, the bond interface cools down 42°C in 20 ms in the 55 mm/s process. During the *same period*, the interface cools down 210°C in the 2000 mm/s process. Here, the melt pool has solidified after only ≈ 3 ms. In the low-speed case, the melt resides > 20 ms (and will continue to do so). It can also be noticed that the tape acts as a “heat source” for the bond interface, due to the high heat soak.

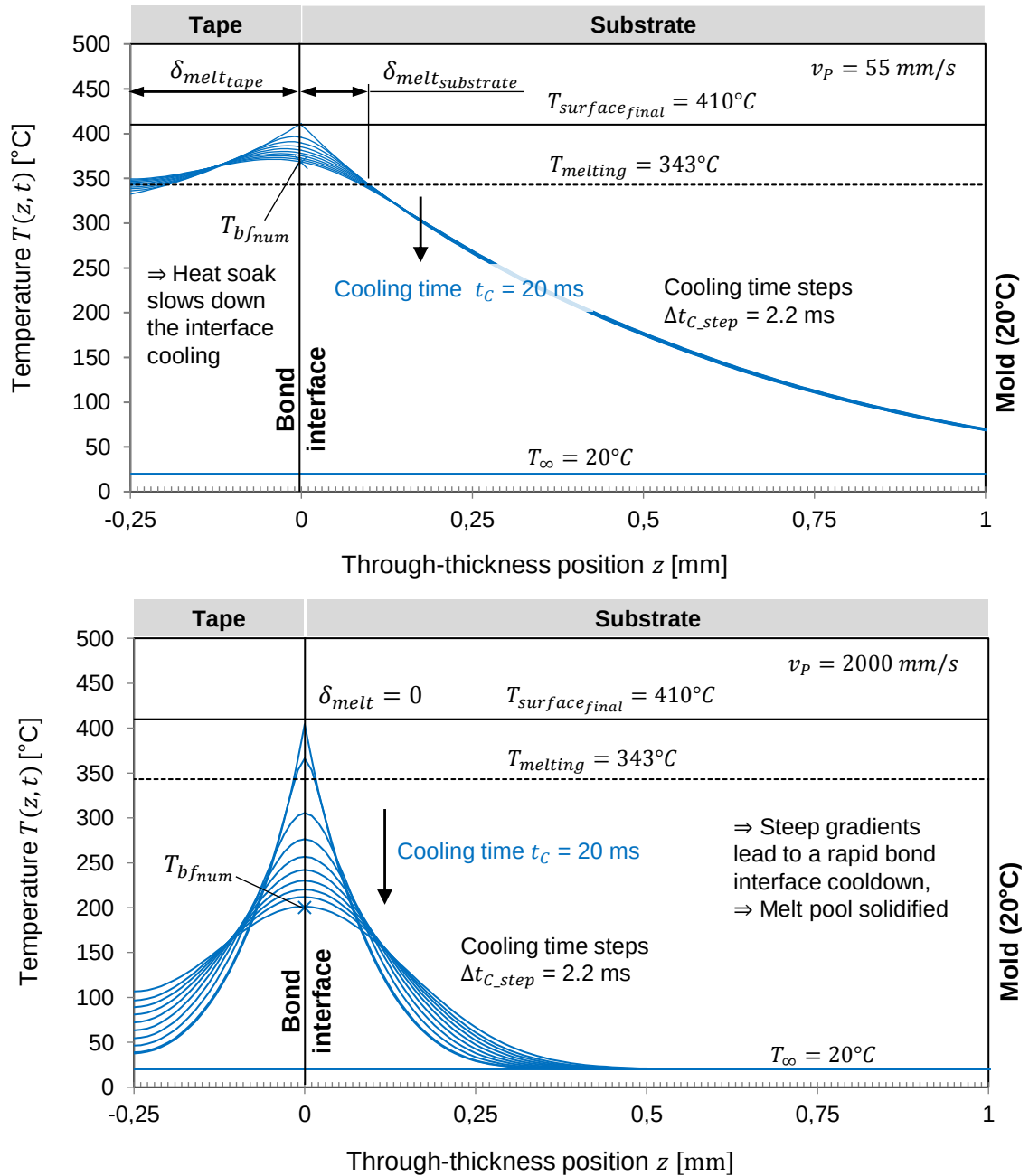


Figure 5.5: Decaying temperature distribution over time within a 0.25 mm-thick tape (left) and a 1 mm-thick substrate (right) after a relatively low process speed of 55 mm/s (top) and a relatively high process speed of 2000 mm/s (bottom); please see in combination with Figure 5.4. Final cooling time is equal (20 ms).

Zeitlich abklingende Temperaturverteilung in einem 0,25 mm dicken Tape (links) und einem 1 mm dicken Substrate (rechts) nach einem relativ langsamen Prozess (oben) und einem relativ schnellen Prozess von 2000 mm/s (unten).

5.2 Heating Characteristic of Tape Thicknesses / Process Speeds

Erwärmungscharakteristik von Tapedicken / Prozessgeschwindigkeiten

The previous sections already revealed a significantly different heating characteristic, depending on whether heat accumulation occurs or not (see Figure 4.9, right-hand side). Surprisingly, this thermal aspect has not been paid much attention to in the literature, although it drastically influences the heating behavior (compare Equation 4.13 and 4.19). Figure 5.6 displays again the surface temperature development $T_{surface}(t)$ of different PEEK/CF bodies – 0.1, 0.15, 0.2, 0.25, 0.3, 0.4 mm and ∞ – for various irradiation times t_L (Equation 4.15) and respective process speeds.

It can be observed that the surface temperature begins to deviate at a certain irradiation time t_L , because the heat accumulation effect occurs (Figure 4.9, p. 64). This thermal behavior was recently demonstrated in experiments by COURTEMANCHE, here caused by a varying thickness along the tape width [COUR17, p. 15-22]. Section 5.4 and 6.2 will present further experiments on this phenomenon. For shorter irradiation times, all bodies converge to the same heating characteristic.

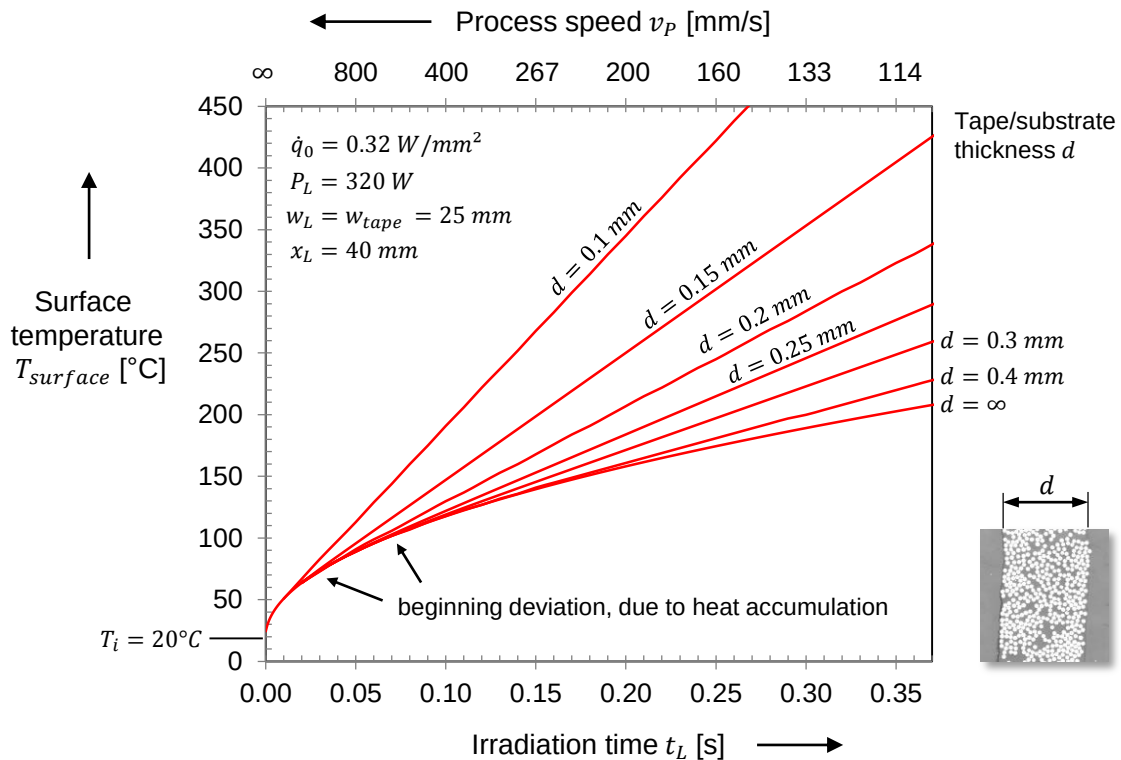


Figure 5.6: Surface temperature development during laser irradiation of fiber-reinforced thermoplastic bodies of different thicknesses (PEEK/CF)

Entwicklung der Oberflächentemperatur während der Laserbestrahlung von faserverstärkten Thermoplastkörpern verschiedener Dicke (PEEK/CF)

Use of Fourier Number. To show under which conditions the heat accumulation effect occurs *in general* for all thicknesses (and process speeds), the Fourier number Fo can be used. The dimensionless number Fo was introduced in the previous section, Equation 4.17. Fo sets the *heat diffusion rate* of a body in relation to its *heat storage rate*. The lower Fo , the less a *heating process* tends towards heat accumulation,

because either the heat diffuses slower within the body, has less time to diffuse or the body is simply thicker. Conversely spoken, heat accumulation tends to occur for:

- long irradiation times t_L (or low speeds v_P), thin bodies d
- high thermal conductivities k_z .
- low specific heat capacities c_p and densities ρ

In the context of thermoplastic tape placement, this means that different tapes/substrates tend to different heat accumulation characteristics. Subsequently, this distinction will be described in general terms for PEEK/CF and HDPE/GF tapes.

Generalization. It is known that the transition point between *semi-infinite* and *finite* cases occurs when $Fo \approx 0.2$ [BERG11, p. 311]. In all possible combinations of t_L , k_z , c_p , ρ and d which lead to $Fo \approx 0.2$, heat just reaches the backside. By substitution of Equation 4.17 into the correlation of process speed, laser irradiation length and time $v_P = x_L/t_L$, we obtain a limit case for heat accumulation in tape placement:

$$v_{P_{lim}}(d, \alpha) \approx \frac{k_z}{\rho c_p} \cdot \frac{x_L}{0.2 \cdot d^2} \quad (5.3)$$

The transition point can be plotted *logarithmically* (Figure 5.7). The graph shows that for common bodies (0.2 to 1 mm) and common process speeds (100-1000 mm/s), heat accumulation is still a rather common phenomenon. A 0.2 mm-thick tape for example requires $\gg 1000$ mm/s to avoid any heat accumulation. The notion that the laser “*just heats up the surface*” is a common misunderstanding about laser-assisted tape placement. It is rather the case that the combination of high laser powers *and* speeds enable *surface melting* via the occurring thermal gradients (see Figure 5.2).

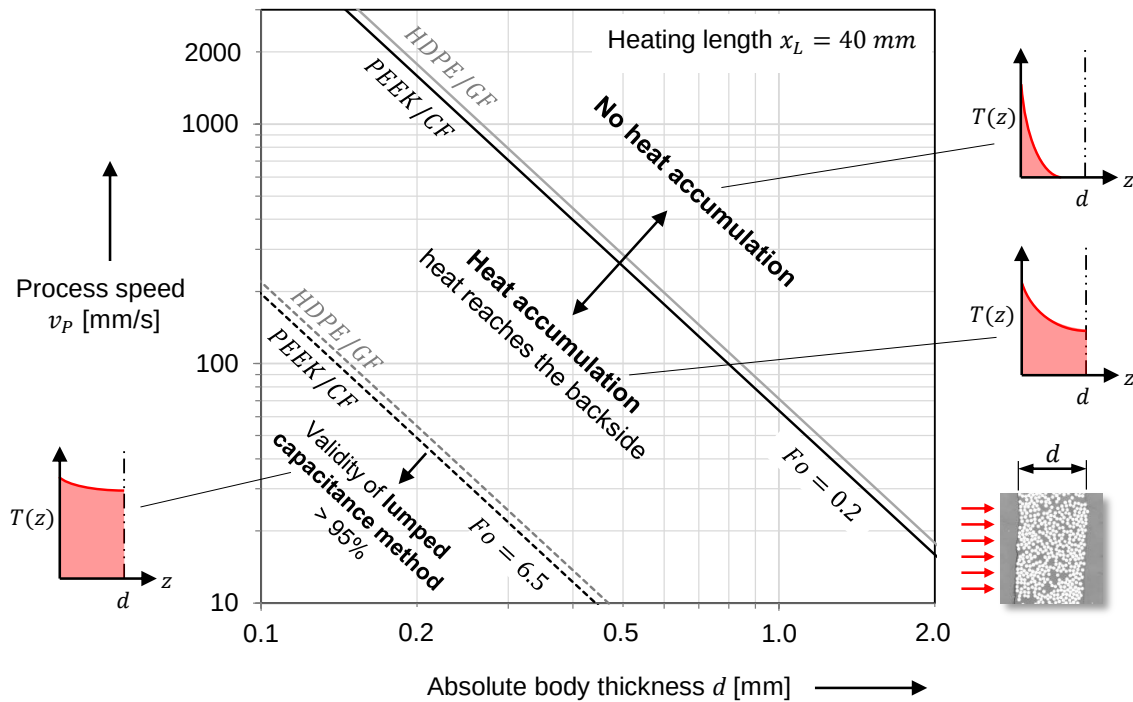


Figure 5.7: Occurrence of the heat accumulation in thermoplastic tapes/substrates
 Auftreten des Wärmestaueffekts in Thermoplast-Tapes/Substraten

5.3 Description of the Temperature Gradient / Heat Soak

Beschreibung des Temperaturgradienten / der Wärmeaufnahme

Temperature Gradient. A *temperature gradient* describes a temperature *difference* over a certain *distance* in space [BEJA01, p. 12]. It causes heat (energy) to flow. Observation of the temperature distribution in Figure 4.9 and Figure 5.2 show that the temperature gradient differs throughout the body thickness, both for the tape and substrate. Only in very slow processes, the temperature gradient is near-constant in the z direction. At higher speeds, it is a location-dependent value and can therefore be obtained by the *derivative* of Equation 4.13 and 4.16:

$$T_{grad}(z) = \left. \frac{dT}{dz} \right|_z \quad (5.4)$$

It was found that measurements of the internal temperature gradient are quite difficult to perform in practice at scales $< 250 \mu\text{m}$ (*quarter of a millimeter*), without disturbing the heat flows, and at time periods $< 50 \text{ ms}$ (*one twentieth of a second*).

Global Temperature Gradient. Instead, it is proposed to use the *global temperature gradient* over the whole body as an index of the prevailing gradients:

$$T_{grad}(0 \rightarrow d) = \frac{T_{surface} - T_{backside}}{\Delta d} \quad (5.5)$$

This value is also useful for practical purposes, because it can be measured by contact-free pyrometers and tape thickness measurements, Figure 5.8.

Temperature Ratio. Another characteristic value for practical purposes is the *ratio* between the temperature of the backside and the surface (front side):

$$K_{\Delta T_{calc}} = \frac{T_{backside} - T_0}{T_{surface} - T_0} = \frac{T(d, t) - T_0}{T(0, t) - T_0}; \quad 0 < K_{\Delta T_{calc}} < 1 \quad (5.6)$$

The factor $K_{\Delta T_{calc}}$ is a dimensionless value between 0 and 1, with 1 being *equilibrium* and 0 being the strongest measureable temperature ratio ($T_{backside_{min}} = T_0 = 20^\circ\text{C}$). $K_{\Delta T_{calc}}$ is a helpful *representation* of the *spectrum* of temperature gradients (Figure 3.2, p. 44). In the following, $K_{\Delta T}$ will be referred to as the *temperature ratio*.

The description of $K_{\Delta T}$ will help to make general statements about the global temperature gradient within a tape. It is possible to determine $K_{\Delta T}$ for different irradiation times t_L by solving Equation 5.6:

$$K_{\Delta T_{calc}}(t_L) = \frac{Fo - \frac{1}{6} - \frac{2}{\pi^2} \cdot \sum_{n=1}^{\infty} \frac{\cos(n\pi)}{n^2} e^{-(n\pi)^2 Fo}}{Fo + \frac{1}{3} - \frac{2}{\pi^2} \cdot \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-(n\pi)^2 Fo}}; \quad Fo = \alpha \cdot \frac{t_L}{d^2} \quad (5.7)$$

The equation shows that (for homogeneous irradiations) the temperature ratio depends only on the irradiation time t_L , the material properties (ρ, c_p, k_z) and the absolute body thickness d – but *not on the magnitude on the surface heat flux* $\dot{q}_0$. It has to be pointed out that thinner tapes of equal $K_{\Delta T}$ exhibit a steeper temperature gradient than thicker tapes. $K_{\Delta T}$ should therefore only be compared among tapes of equal thickness.

5.4 Experimental Investigations

Experimentelle Untersuchungen

Validation Approach. The presented calculations require experimental validation. Direct measurement of the transient temperature distribution $T(z, t)$ within the material at the scales of interest ($< 250 \mu\text{m}$ / $< 50 \text{ms}$) was found to be quite difficult to conduct in practice for several reasons: First of all, the slicing of the already thin tapes into thinner pieces is almost impossible without changing the attributes of the probe. Also, even the thinnest commercially available thermocouples were found to be comparably thick: $> 250 \mu\text{m}$ [WATL17, p. 20]. LEVY et al. concluded that the use of *contacting* temperature sensors, like thermocouples, was inappropriate, as those significantly disturb the heat flow by introducing thermal resistances [LEVY12a]. Additionally, the lowest response time of the thinnest thermocouples (in water) is still $> 20 \text{ms}$ (at just 63% of the measured temperature level) [WATL17, p. 20]. Lastly, the use of *similitude theory* on *thicker* probes was not possible, because the required temperature gradients would lead to high surface temperatures, thus igniting the polymer. (Temperature distributions behave *self-similar* at different geometrical scales.)

In the literature, most investigations of the through-thickness temperature distribution have focused on measurements within the thicker substrate, at scales $> d_{\text{tape}}$. In addition, the so-far investigated processes at conventional speeds $< 500 \text{mm/s}$ exhibited relatively flat temperature gradients, so it was a lot simpler to achieve a sufficient resolution [HASS05 p. 877] [LEVY12a] [KERM15, p. 58-59] [KUGE16].

Practical Solution. Instead of direct measurement within the material, the temperature distribution is therefore inferred from temperature measurements of the front and backside of a tape. Figure 5.8 shows the principle measurement setup. A magnification of the setup is shown in the Appendix, Figure 15.1 (p. 177). A similar method was used in [STIM14, p. 56-57], however for a different purpose: STIMPFL used the experimental setup to determine the transmissivity of a non-blackened glass-fiber tape.

From the *changing relation* between the front side temperature T_{surface} and the backside temperature T_{backside} at shorter irradiation times t_L , it is possible to measure *shifts* of the *temperature gradient*, which were predicted in the previous sections.

Irradiation. The laser heating was done statically, without movement of the material. Convective heat losses were shown to be negligible, because the thermal resistance of convection is orders of magnitude higher than the internal thermal resistance by conduction (Section 4.3). Also, the heat transfer coefficient remains nearly constant at increasing speeds. This was found in another prestudy (Section 19.1 in the Appendix). The respective quasi process speeds $v_{P_{\text{quasi}}}$ can be calculated by $v_{P_{\text{quasi}}} = t_L / x_{L_{\text{quasi}}}$.

Material Choice. As material, PEEK/CF of 0.15 mm thickness was chosen, to compare the findings of the analytical and numerical models. To get insights on the effect of the tape thickness, HDPE/GF of 0.25 mm thickness was used.

Sensors. The surface temperature was obtained by contact-free pyrometers. For more information on the devices please see Section 17.3 (Appendix). The pyrometers enabled a minimum sampling time of 1.5 ms, which was necessary during the investigations of strong temperature gradients at short irradiation times. The pyrometers were placed above and below the tape in perspective angles of $> 45^\circ$, to avoid false measurements by the angular dependency of the surface radiation (*Lambert's law*). Note that the pyrometers detect only above a certain level (74°C).

Heating Source. The heating laser source was a VCSEL module with 1.6 kW maximum power and 1.2 W/mm^2 maximum irradiation intensity (Appendix, Figure 17.1, p. 185). The available laser power predefines the maximum magnitude of temperature gradients, which can be induced (Figure 5.1, 5.2). The absorption coefficient of PEEK/CF tapes for laser wavelengths of 980 nm is reported to be $> 90\%$ [KOEL08, p. 51] [STOK14, p. 106] (and others). Losses by reflection are $< 10\%$.

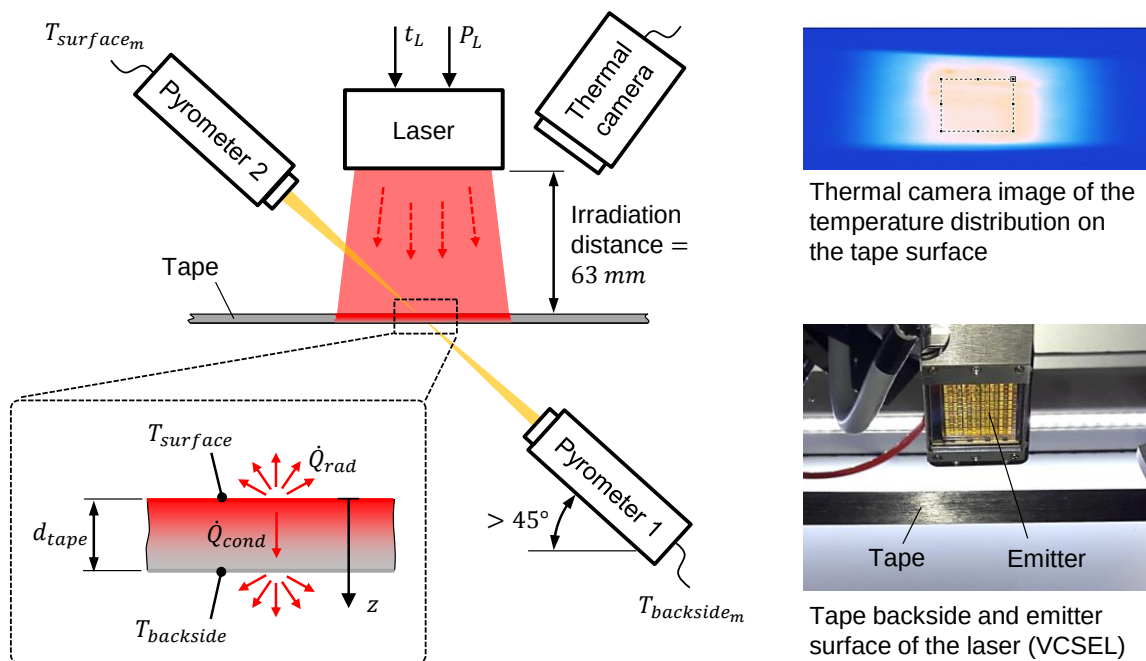


Figure 5.8: Experimental setup for the determination of temperature gradients in thin fiber-reinforced thermoplastic tapes; extended pictures in the Appendix (p. 177)
Versuchsaufbau zur Ermittlung der Temperaturgradienten in dünnen faser-verstärkten Thermoplast-Bändern; erweiterte Abbildungen im Anhang (S. 177)

Irradiation Distance. The laser was positioned perpendicular to the tape with an irradiation distance of 63 mm. The distance was necessary to achieve a homogeneous irradiation distribution at the surface, yet maximum irradiation intensity. The distance (63 mm) was found to be a good compromise between high irradiation intensity ($\approx 1 \text{ W/mm}^2$) and good homogeneity.

The distance was determined in prestudies, by optical simulations, based on the works in [WEIL16b] and comparative surface temperature measurements (Figure 5.9 and Appendix, Figure 16.1, p. 181). Too close positioning of the VCSEL makes the single emitter blocks appear at the target surface. It should be made clear that the novel possibility of VCSEL – adjustable irradiation – was not required for this experiment.

Homogeneity Validation. The pyrometers were supplemented by a thermal imaging camera for inspection of the surface temperature *homogeneity*. These measurements had two purposes: (1) validation of the *irradiation homogeneity* of the VCSEL and (2) investigation of the *heat flow homogeneity* into the probe (tape).

Measurements were carried out on two different tapes (PEEK/CF, 0.15 mm; HDPE/GF, 0.25 mm) and in three different combinations of irradiation time t_L and laser power P_L . The tapes are industry standards and offered a seemingly homogeneous fiber distribution (see Appendix Figure 18.1 and Figure 18.2, p. 187, 188).

The results of the measurements are shown on the next page, Figure 5.9. The surface temperatures are measured on a rectangular of 20 x 25 mm; obvious local inhomogeneities were left out (see for example top-right in the figure). The homogeneity was quantified by the relation between maximum and minimum measured temperature:

$$\Delta T_{rel_m} = \left(1 - \frac{T_{surface_{max}} - T_i}{T_{surface_{min}} - T_i} \right) \cdot 100\%; \quad T_i = T_0 = 20^\circ\text{C} \quad (5.8)$$

Observations. It was found that the heating of the PEEK/CF tape led to a maximum surface temperature difference of 29.6°C with a relative difference of ΔT_{rel_m} of 13%. The heating of the HDPE/GF tape showed a maximum temperature difference of 6.8°C with ΔT_{rel_m} of 8% (Figure 5.9). The differences can have two causations:

- A) The temperature distribution is as non-homogeneous as measured and is caused by non-homogeneous through-thickness heat flow, caused by thickness variations over the width or a non-homogeneous fiber distribution.
- B) The temperature distribution is homogeneous, but the surface *emissivity* is non-homogeneous. This could be caused by varying surface properties.

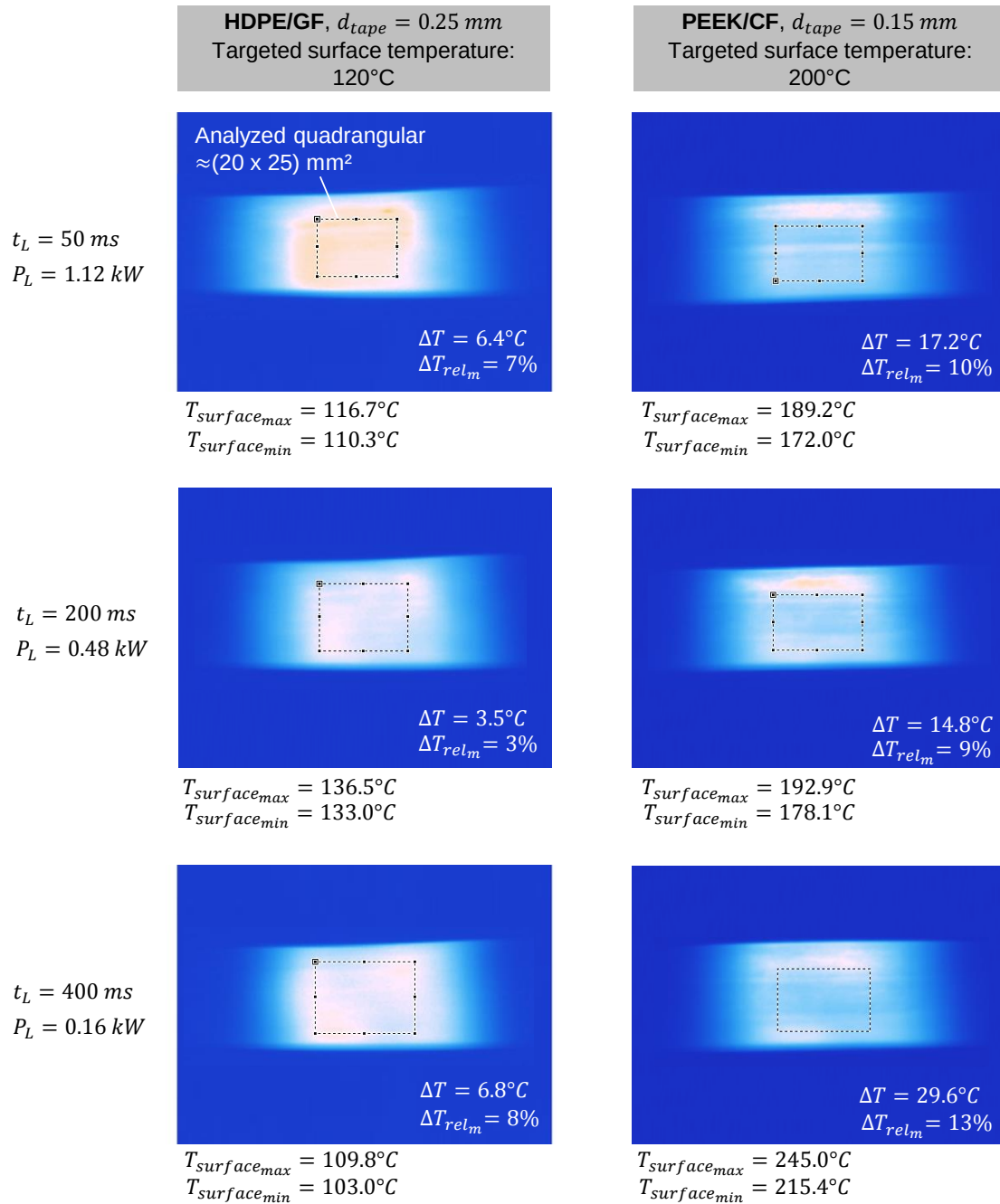
Further *specific research* is required to answer this open question. Apart from this subtopic, the measurements provide proof that *no significant temperature variation* prevails along the width of the tape. The tape properties are such that a heating within a surface temperature window of (at least) $\pm 7\%$ is possible. In general, this is a positive result for the processability of industry-standard tapes.

However, the measured tolerances permit qualification of the simplified model against the detailed model, *because the model predictions differ less from each other, than the measured surface temperature homogeneity* itself (Table 4.4). It is possible that the pyrometer detects a variation between surface and backside, which is solely caused by this inhomogeneity, not by any thermal phenomena. The prediction accuracy of the simplified model is therefore *within the window of practical tolerances*.

Notwithstanding the above, the issue does not impede measurements of the *changing temperature gradients* at higher laser powers and shorter irradiation times (higher process speeds). To determine the gradient, the temperature history of surface and backside was measured. The relation of the two values after the heating cycle gave insight on the prevailing temperature *ratio* and is defined as:

$$K_{\Delta T_m} = \frac{T_{backside_m} - T_0}{T_{surface_m} - T_0}; \quad T_0 = 20^\circ\text{C} \quad (5.9)$$

The factor is a dimensionless number between 0 and 1.



t_L : Irradiation (heating) time P_L : Laser power Laser: VCSEL Irradiation distance = 63 mm

Figure 5.9: Thermal camera images for the determination of homogeneity of surface temperature of two different tapes

Thermokamera-Aufnahmen zur Ermittlung der Homogenität der Oberflächen-temperatur zweier unterschiedlicher Tapes

The *sampling rate* of the thermal imaging camera – 15 ms – was found to be too low for the time scales of interest (< 10 ms). The use of faster pyrometers was inevitable.

Figure 5.10 shows the temperature development of the surface and backside in the time domain. Three different combinations of laser power P_L and irradiation time t_L are depicted. The three cases are also shown magnified on the next page in combination with the linear-approximated temperature gradients in the through-thickness direction z , both for the heating and the cooling period (Figure 5.11, next page).

Observations. The general difference in thermal penetration is already revealed by the larger difference between surface and backside temperature for the highest laser power (1): It can be observed that 25% of the surface cooling occurs via internal conduction (relative to 20°C), until a quasi equilibrium is reached. The internal cooling at lower laser powers (/speeds) – (2) and (3) – is much smaller: 7% and 2%.

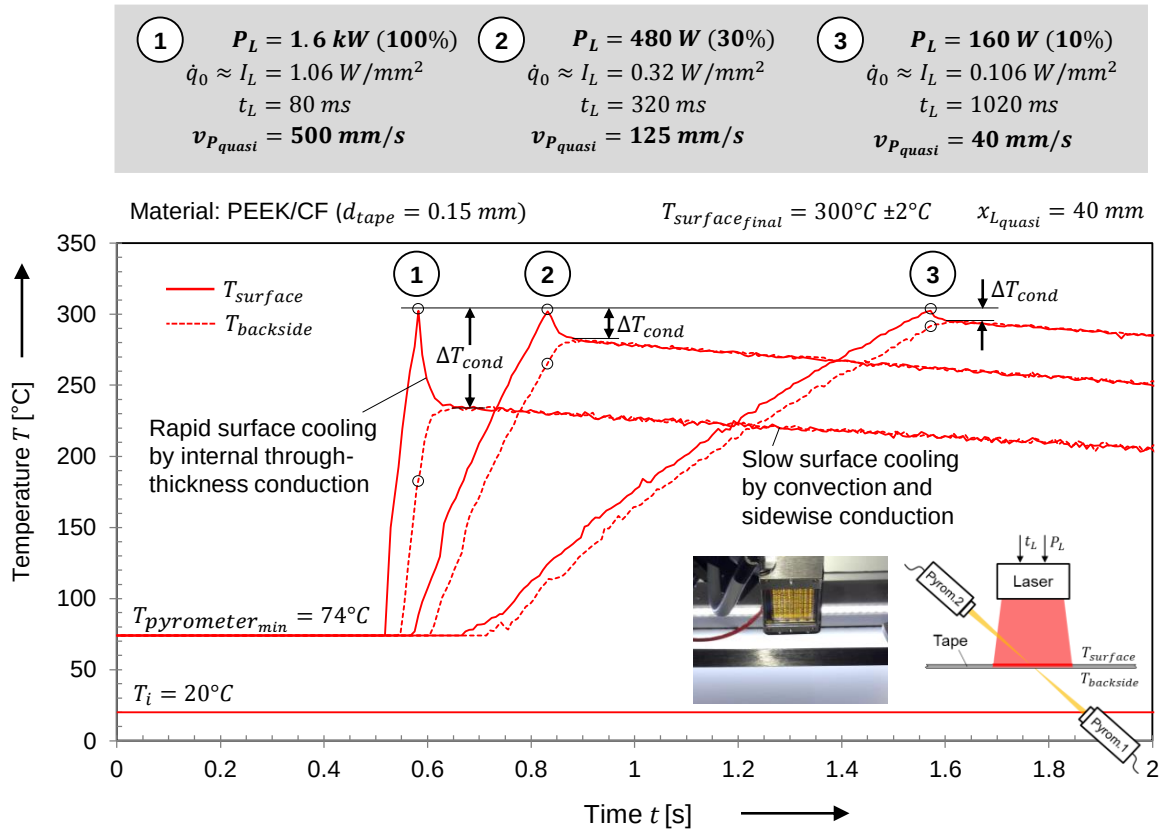


Figure 5.10: Tape heating and cooling characteristic of three different laser powers and irradiation times ($\sim$ to process speeds); final surface temperatures are equal

Tape-Erwärmungs- und Abkühlcharakteristik für drei verschiedene Laserleistungen und Bestrahlungszeiten (antiproportional zur Prozessgeschwindigkeiten); finale Oberflächentemperatur ist in allen Erwärmungsprozessen gleich

The internal cooling by conduction ΔT_{cond} increased by a factor of ≈ 3.5 from 320 ms to 80 ms (irradiation time), and by a factor of ≈ 12 from 1020 ms to 80 ms, caused by a steeper temperature gradient $(T_{surface} - T_{backside})/d_{tape}$. After the decay of the temperature gradient (by internal conduction), convective and sidewise cooling in fiber direction sets in, but at much lower rates (only 20°C per second).

These findings proof the assumptions made in Section 4.3 that the short-time surface cooling process is dominated by internal cooling via through-thickness conduction.

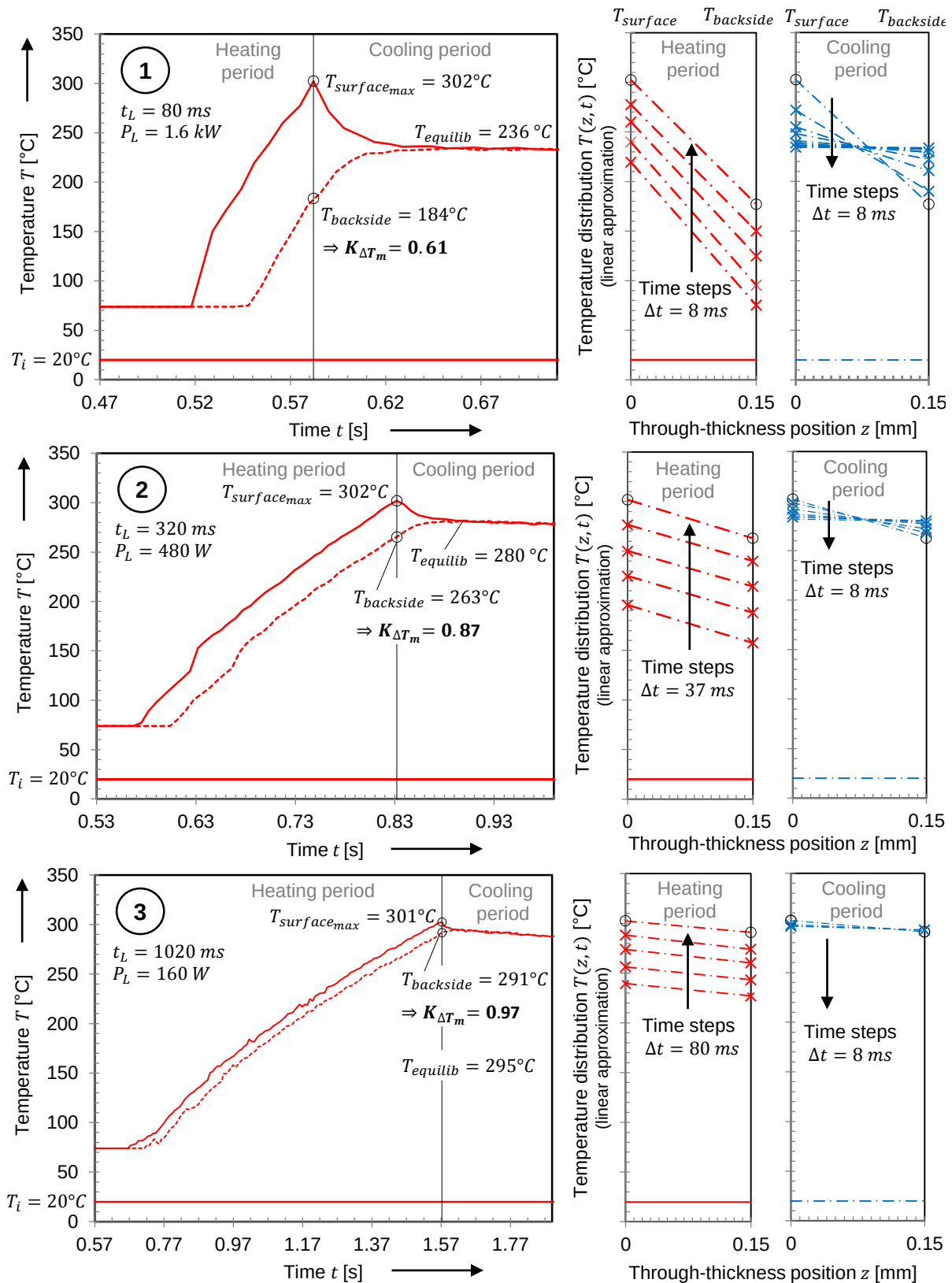


Figure 5.11: Measured temperature gradients with in a 0.15 mm-thick tape at three different combinations of laser power and irradiation time (inversely proportional to the process speed), before and during cooling. Final surface temperature $\approx 300^\circ\text{C}$.
Gemessene Temperaturgradienten in einem 0,15 mm dicken Tape bei drei verschiedenen Kombinationen von Laserleistung und Bestrahlungszeit (antiproportional zur Prozessgeschwindigkeit), vor und während der Abkühlung. Finale Oberflächentemperatur: $\approx 300^\circ\text{C}$.

Extended Considerations. Further measurements were conducted with various irradiation times and laser powers, for the final surface temperatures 200°C and 150°C, to reinforce the analytical model predictions. The results are plotted in Figure 5.12 (red curves at the top) in comparison to the model predictions (simplified analytical).

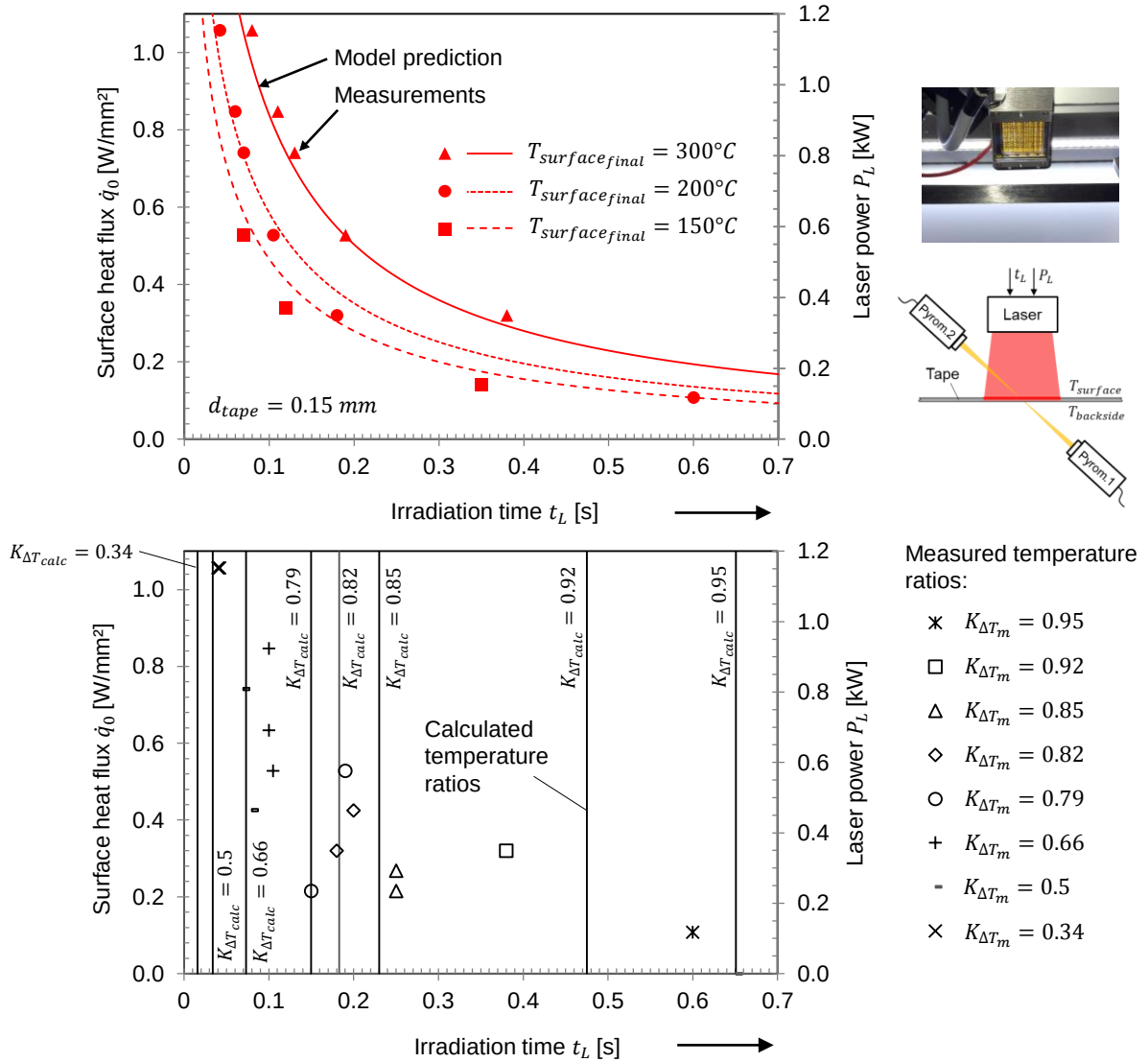


Figure 5.12: Top: Measurements of final surface temperatures for various combinations of irradiation time and surface heat flux ($\sim$ laser powers). Bottom: Temperature ratios from measurements in comparison with analytically determined ratios

Oben: Messungen der finalen Oberflächentemperatur für verschiedene Kombinationen aus Bestrahlungszeit und Oberflächenwärmestromdichte ($\sim$ Laserleistung); Unten: abgeleitete Temperaturverhältnisse der Messungen im Vergleich zu analytisch ermittelten Temperaturverhältnissen

The graph was supplemented by the measured temperature ratios $K_{\Delta T}$, which were derived from Equation 5.9, and its calculation, using Equation 5.6 from Section 5.2. The analytical model yields surface temperatures and temperature ratios, which are in suitable agreement with the experimental results. The remaining deviations could be caused by the presented tolerances in the measurement setup and tolerances in the material property data, which can have a sensitive effect.

Nevertheless, for practical purposes it is relevant to have a quantitative description of *how with increasing process speeds and consequently shorter irradiation times, yet equal final surface temperatures (by controlled increased laser power), the internal temperature gradient increases.*

Interim Conclusions. The experiments confirm the assumptions made by both the simplified analytical and detailed numerical analysis. Due to the presented validation, the models were used for further (more detailed) investigations. The next section will shift the focus on the melt pool, its depth, length and dwell time $\delta_{melt}, x_{melt}, t_{melt}$.

It was further shown that *conduction* in the *through-thickness direction* accounts for more than 90% of the heating *and* cooling behavior in laser-assisted tape placement. Therefore, it seems to make sense to shift the research focus more on the through-thickness domain $T(z)$ in the future, instead of the feed direction $T(x)$.

5.5 Melt Pool Depth

Schmelzbadtiefe

Determination by Linear Approximated Analytical Solution

In order to obtain the melt pool depth δ_{melt} after heating, Equations 4.13 and 4.16 can be rearranged to the melting temperature $T_{melting}$ and solved to z :

$$T(z, t_L) = T_{melting} \quad \Rightarrow \quad z(T_{melting}, t_L) = \delta_{melt} \quad (5.10)$$

However, this is difficult to achieve analytically, as there is no available *inverse function* for the *error function* $ierfc(X)$. Graphical analysis can be used alternatively to determine the melt pool depth from graphs, e.g. Figure 5.2. However, this is tedious work and can take up a lot of time. Therefore, an analytical approximation is proposed:

Approximation. Figure 4.8 has already illustrated that for a non-preheated tape or substrate, the temperature distribution near the surface is similar to the magnitude of the surface heat flux $\dot{q}_0$ divided by the conductivity k_z . With consideration of the known final surface temperature $T_{surface_final}$, the correlation can be written as:

$$T(z) \approx \left. \frac{dT}{dz} \right|_{z=0} \cdot z + T_{surface_final}; \quad \left. \frac{dT}{dz} \right|_{z=0} = -\frac{\dot{q}_0}{k_z} \quad (5.11)$$

within the following processing window:

$$T_{melting} < T_{surface_final} < T_{degradation} \quad (5.12)$$

which is the common case for in-situ tape placement. Therefore, the following correlation applies for the melt pool depth δ_{melt} :

$$\delta_{melt} \approx -k_z \cdot \frac{T_{melting} - T_{surface_final}}{\dot{q}_0}; \quad \dot{q}_0 = \frac{P_L}{A_L} \quad (5.13)$$

From the correlation of Equation 5.13, a first observation can be made: Increasing the final surface temperature $T_{surface_final}$ by increasing the laser power P_L , generally yields to a deepening of the molten pool δ_{melt} . However, for melt pool control, this strategy is

restricted at the point when the surface temperature exceeds the degradation temperature of the polymer ($T_{degradation}$). Other ways have to be found to change the temperature *distribution* $T(z)$ not only by its temperature *level*, but also by its *shape*. This will be the topic of later chapters (Chapter 7 and 8).

If the backside temperature exceeds the melting temperature of the polymer, the melt pool depth δ_{melt} equals the thickness of the tape d_{tape} :

$$T_{backside} = T_{melting} \quad \Rightarrow \quad \delta_{melt} = d_{tape} \quad (5.14)$$

The tape is *completely molten* in this case. Complete melting of the tape has certain pros and cons, which are summarized in Table 14.1 (Appendix, p. 175).

Section 5.1 already presented results for the melt pool depth for three distinct process speeds (Table 5.1). In general, it was observed that the melt pool depth δ_{melt} decreases at higher process speeds; how exactly will be investigated in the following.

Analysis of Higher Process Speeds

Use of Linear Approximated Analytical Solutions. The direct measurement of the melt pool depth was found to be difficult to conduct, because the thin tapes do not allow for sensor embedding without significantly disturbing the heat flows. The polymer melt pool does also leave no significant signature after solidification, like Martensite does in metal hardening (which can be detected in microsections). For these reasons, the melt pool depth will be derived from analysis of the previously validated thermal models, as currently no methods are known to obtain it directly via measurements.

To be able to determine the melt pool depth δ_{melt} for various process speeds v_p , yet equal final surface temperatures $T_{surface_{final}}$, Equation 5.13 is used with results of Equation 5.1 for the required surface heat flux $\dot{q}_0$. The results are plotted in Figure 5.13 on the next page. The through-thickness direction is vertically oriented here, to keep the x-axis for the variable (process speed). The upper graph shows the melt pool depth δ_{melt} for a 0.15 mm-thick PEEK/CF tape; the lower graph for a semi-infinite substrate. On the right-hand side, a true-to-scale schematic drawing of a microsection is depicted, to show the relation to typical near-surface conditions.

Two analyses of the melt pool depth are presented: one in which the final surface temperature is set to 410°C (minimum case) and a second case in which it is set to 550°C (maximum case). In the first case, the minimum overheating temperature is 67°C; in the second, the *safety buffer* to the definite degradation temperature (600°C) is 50°C.

Observations. A continuous decline of the melt pool depth can be observed. The effect is root-caused by the fixed thermal diffusivity of the material (please compare Figure 5.2). The graphs show that with higher speeds it becomes inevitable that the melt pool depth converges to zero: $v_p \uparrow \Rightarrow \delta_{melt} \rightarrow 0$. It can also be observed that at speeds < 250 mm/s the tape is molten deeper than the substrate, because the heat accumulation effect in the tape creates flatter temperature gradients.

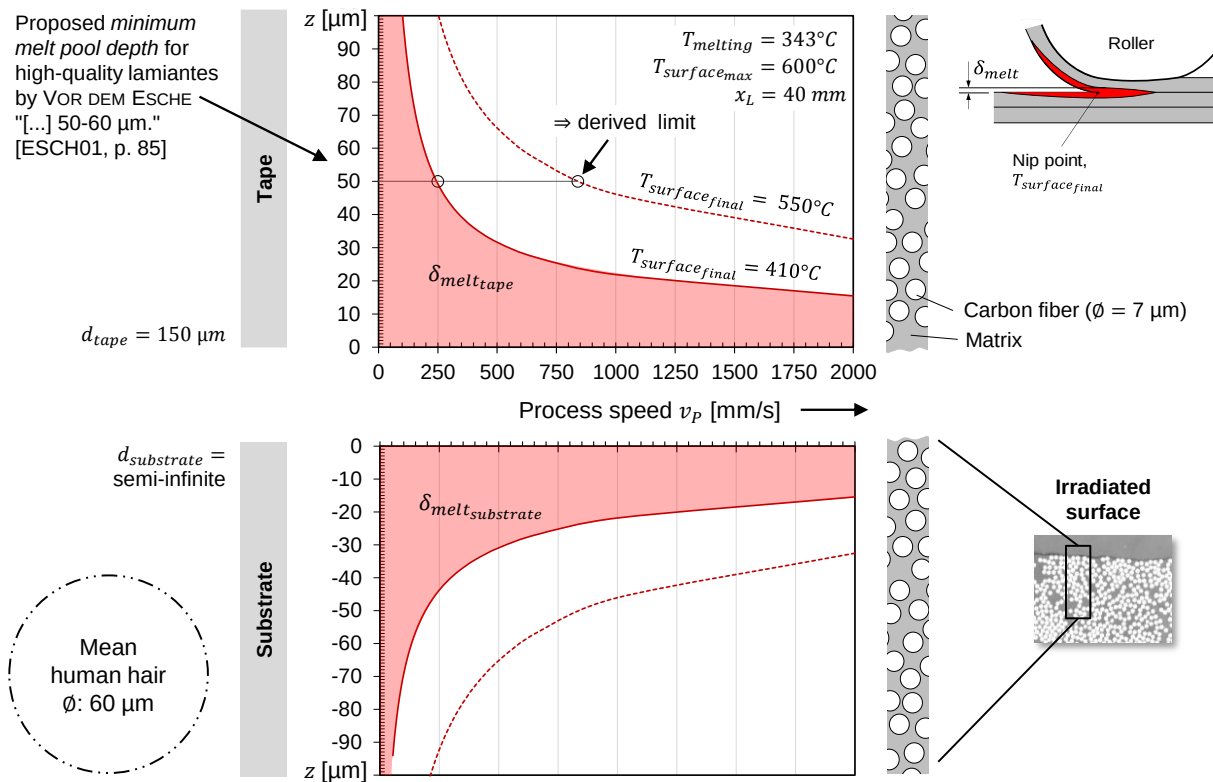


Figure 5.13: Melt pool depth approximation after heating for increasing process speeds with the boundary condition of equal final surface temperature after heating (PEEK/CF). Please consider in combination with Figure 5.2, p. 74.

Näherung der Schmelzbadtiefe nach der Erwärmung für zunehmende Prozessgeschwindigkeiten mit Randbedingung gleicher finaler Oberflächentemperatur

Impact on the Bonding Process. According to VOR DEM ESCHE, a melt pool depth of at least 50-60 μm is required to achieve high-quality laminates [ESCH01, p. 85]. If this is true, the PEEK/CF process is limited at ≈ 800 mm/s. However, the limit probably depends on a multitude of material properties, like surface roughness or melting temperature. The issue of high-speed bonding will be addressed in Section 6.1.

Near-Surface Condition. Please note that the thermal model is based on *composite* material properties. This assumption neglects *inhomogeneities* at the surface, where in many cases a polymer layer of up to 25 μm is present (see Figure 18.2, p. 188). At this scale, the polymer has a lower thermal diffusivity α than the composite ($\approx$ factor 2), so with higher speeds, the melt pool depth will become dominated by the slower heat diffusion of the polymer. The melt pool δ_{melt} will converge to zero earlier.

Figure 21.2 (p. 202) shows a magnification of a typical tape surface. Bulks of polymer can be identified in depths of > 20 μm . With the melt pool converging towards the thickness of the surface polymer at > 1000 mm/s, computing with composite material properties becomes less precise. A simulation of the micro heat flow is recommended.

Optical Aspects. In an even more detailed consideration, the laser penetration could be considered as well, due to volumetric absorption in the surface polymer $\dot{q}_0(z)$. The laser absorption in z decreases exponentially within the polymer and is absorbed at the first layer of carbon fibers at the latest [SCHL04b] [GROU12, p. 13].

Assessment of the Approximated Solution. A linear approximation for the determination of the melt pool depth δ_{melt} was proposed (Equation 5.13). Like any approximation, the equation will generate deviations under certain conditions. This subject will be evaluated in the following.

Figure 5.14 shows the typical case of a heated PEEK/CF tape of 0.15 mm thickness and that of a heated substrate of 1 mm thickness. Both bodies have reached a surface temperature of 410°C. Geometrically spoken, Equation 5.13 obtains the melt pool depth δ_{melt} at the *intersection* of the temperature distribution $T(z)$ with the melting temperature $T_{melting}$ (top-left in the figure). The *absolute* deviation of the approximation can be derived by its subtraction from the actual temperature distribution (Equation 4.13 and 4.16), shown by the hatched areas. The deviation is generally highest when $T_{backside} = T_{melting}$ and for large differences between $T_{surface}$ and $T_{melting}$.

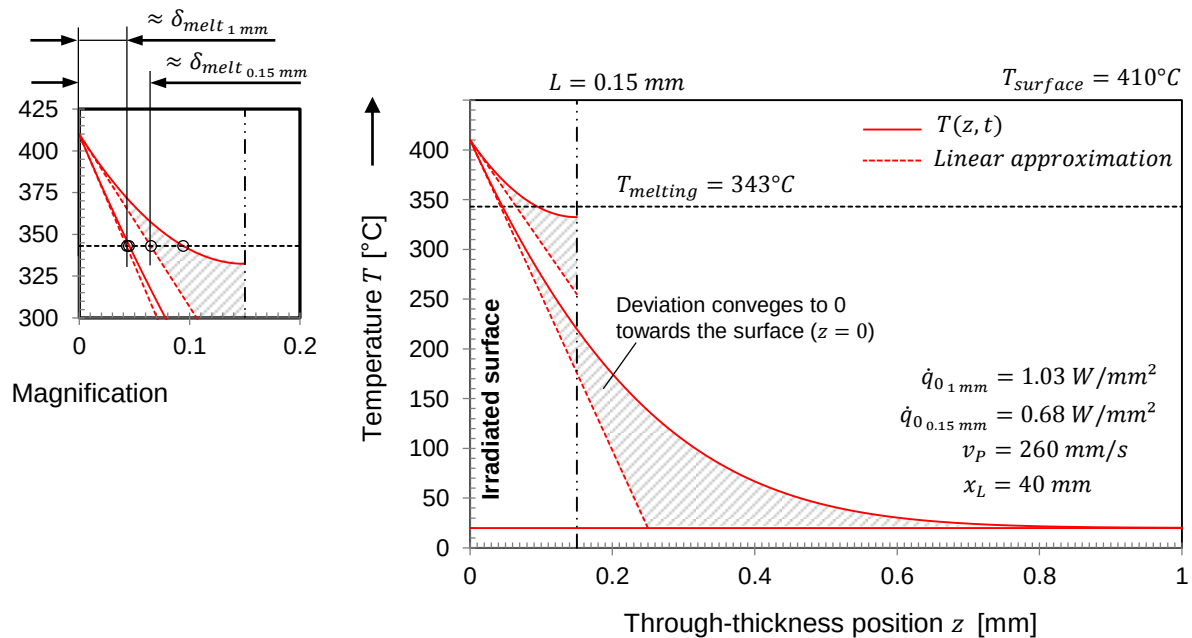


Figure 5.14: Deviation of the linear through-thickness temperature approximation. It converges to zero near the irradiated surface, where the melt pool prevails.

Abweichung der linearen Näherung des Temperaturverlaufs in Dickenrichtung. Diese konvergiert gegen Null hin zur bestrahlten Oberfläche, dort wo das Schmelzbad vorliegt.

The deviation of the linear approximation increases with deeper through-thickness position z . However, the melt pool prevails near the tape surface. Here, the linear approximation and $T(z)$ converge. Therefore, the error is small. With steeper temperature gradients, the error shrinks more, because then $T(z)$ is of a more linear shape (compare Figure 5.2). It is also beneficial that during in-situ tape placement the melt pool depth is generally smaller than the tape thickness ($\delta_{melt} < d_{tape}$).

An experimental determination of the melt pool depth was found to be difficult to conduct, due to the practical issues described in Section 5.4. Measuring the melt pool *directly* could be of high interest for future investigations.

5.6 Melt Pool Dwell Time and Length

Schmelzbadverbleibzeit und -länge

Determination by Analytical Solutions

The analytical solutions for the cooling phase – Subsection 4.3.5 – can also be used to approximate the melt dwell time t_{melt} . In general, the melt pool is solidified when the surface temperature has decreased below the melting temperature of the polymer (compare Figure 5.2):

$$T_{bf}(t_C) = T_{melting} \Rightarrow \delta_{melt} = 0 \Rightarrow t_C = t_{melt} \quad (5.15)$$

Graphical solutions can be utilized to derive t_{melt} , e.g. from Figure 4.10. Alternatively, Equation 4.25 can be solved for the cooling time t_C . Depending on the heating case (Table 4.2, p. 61), this task is difficult to perform when a finite problem prevails, because here, the additivity formula of Equation 4.24 has to be rearranged for t_C .

Still, for the Case C (Table 4.2) the equation can be solved (Equation 4.13). In this case, *both* tape and substrate are described as semi-infinite bodies. We can use the circumstance that $z = 0$ for the surface temperature; the cooling time t_C is defined as $t_P - t_L = t_C$, with t_P as the overall considered time:

$$\begin{aligned} T_{bf} = T_{surface} &= T(0, t_L, t_P) = T_{melting} \\ &= T_0 + \frac{2 \cdot \dot{q}_0}{k_z} \left(ierfc(0) \sqrt{\alpha(t_C + t_L)} - ierfc(0) \sqrt{\alpha t_C} \right) \end{aligned} \quad (5.16)$$

An intermediate result yields to:

$$\frac{k_z(T_{melting} - T_0)}{2 \cdot \dot{q}_0 \cdot ierfc(0) \cdot \sqrt{\alpha}} = \sqrt{t_C + t_L} - \sqrt{t_C}; \quad (5.17)$$

With further rearrangements to t_C and $t_C = t_{melt}$, we obtain:

$$t_{melt}(v_P) = \frac{\left(k_z^2 T_{melting}^2 - 2k_z^2 T_{melting} T_0 + k_z^2 T_0^2 - 4 \cdot \dot{q}_0^2 \cdot ierfc^2(0) \cdot \alpha \cdot t_L \right)^2}{16 \cdot \dot{q}_0^2 \cdot ierfc^2(0) \cdot \alpha \cdot k_z^2 (T_{melting} - T_0)^2} \quad (5.18)$$

where $ierfc^2(0) = (1/\sqrt{\pi})^2 \approx 0.318$ and $v_P = x_L/t_L$. The approximation is especially accurate, when tape and substrate exhibit *symmetrical* temperature profiles. Previous analyses already showed that this is the case for high-speed processes (Figure 5.3). In general, we can conclude that *the melt pool dwell time is proportional to the laser irradiation time: $t_{melt} \sim t_L$ and therefore inversely proportional to the process speed v_P .*

Analysis of Higher Process Speeds

The following section will analyze the effect of the process speed v_P on the melt dwell time t_{melt} . Again, the final surface temperature is kept at a constant level in all considered cases. The boundary condition is a well-functioning control system, which keeps the surface temperature at a defined value. As in previous sections, the setpoint value is 410°C, with an overheating temperature of 67°C for a PEEK/CF ($T_{melting} = 343^\circ\text{C}$).

Melt Dwell Time. The melt dwell time is derived in two ways: (1) with the approximated analytical solution (Equation 5.18, previous page), and (2) with the detailed numerical solution from Section 4.2. A number of six numerical results were derived for 50, 250, 500, 1000, 1500 and 2000 mm/s. The results were fitted by the following equation:

$$t_{melt}(v_P) = 7.3 \cdot v_P^{-1.19} \approx 7.3 \cdot 1/v_P \quad (5.19)$$

and are plotted in the subsequent figure.

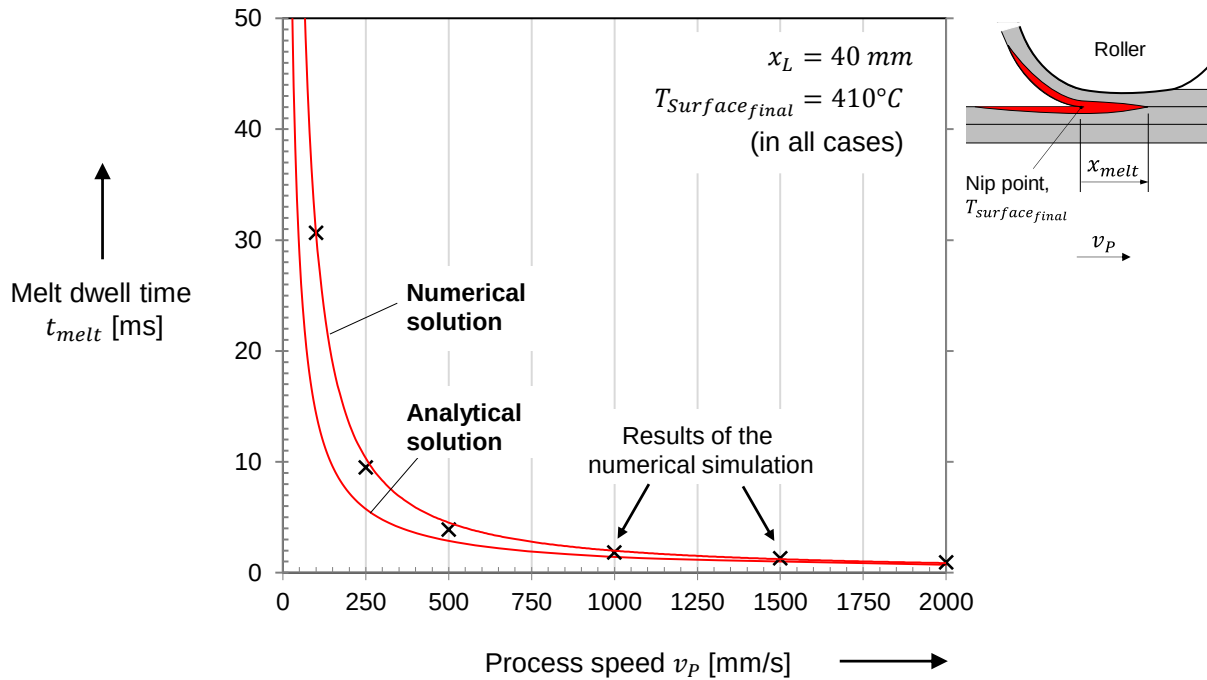


Figure 5.15: Melt pool dwell time for different process speeds but equal surface temperatures
Schmelzbadverbleibzeit bei verschiedenen Prozessgeschwindigkeiten jedoch gleicher finaler Oberflächentemperatur

It can be observed that the melt dwell time t_{melt} decreases significantly over the considered process speeds range. Comparing 100 to 1000 mm/s (factor of 10), the melt dwell time decreases by a factor of 15 and will continue to do so with increasing process speeds. The phenomenon is caused by the increasing temperature gradients through the body thickness z (compare Figure 5.2 to Figure 5.5, p. 78).

The difference between the analytical and the numerical solution arises from the fact that the numerical solution considers the substrate *in contact* with the tape. At lower speeds, the tape is more soaked with heat, therefore acting as a quasi “heat source” for the bond interface during cooling (compare Figure 5.3). At higher speeds and lower heat soaks of the tape, the deviation of the calculation converges to zero.

Melt Dwell Length. The melt dwell *length* x_{melt} , Figure 5.15 (top-right), is derived by:

$$x_{melt} = t_{melt} \cdot v_P, \quad t_{melt} = f(v_P), \quad \Rightarrow x_{melt}(v_P) \approx const \quad (5.20)$$

It turns out that the melt dwell length x_{melt} *stays nearly equal with increasing speeds*, because t_{melt} decreases with $\approx 1/v_P$ (Equation 5.19), but simultaneously increases with v_P (Equation 2.4) by the faster mass flow: $\Rightarrow x_{melt} \approx constant$ over v_P .

5.7 Bond Interface Cooling Rate

Fügeflächen-Abkühlrate

The cooling rate of the bond interface dT_{bf}/dt_c is an essential value in thermoplastic tape placement processes. It correlates inversely to the previously described melt pool dwell time; the slower the bond interface cools down, the longer the melt resides. It also influences other aspects, like the crystallinity (Subsection 6.1.5).

Near-Surface Gradient ~ Cooling Rate. The bond interface cooling rate can be estimated by the temperature gradient near the surface, which is approximately the surface heat flux divided by the conductivity (Equation 5.11, Figure 4.8) and because *heat diffuses away from the bond interface proportionally to the prevailing temperature gradients*, according to Newton's Law of Cooling, Equation 4.6. This approximation is especially true for high process speeds (please compare Figure 5.2 and Figure 5.3).

Laser Power ~ Cooling Rate. It is therefore feasible to state that the bond interface cooling rate is simply proportional to the setpoint value of the laser power P_L , because P_L is a function the process speed v_L (compare Figure 5.1, p. 72):

$$\frac{dT_{bf}}{dt_c} \sim \left. \frac{dT_{bf}}{dz} \right|_{z=0} = \frac{\dot{q}_0}{k_z} = \frac{P_L}{k_z \cdot A_L}; \quad \Rightarrow \frac{dT_{bf}}{dt_c} \sim P_L \quad (5.21)$$

under the boundary condition of a well-functioning control system, which is able to keep the final surface temperature at a constant level (Section 2.3).

The correlation in Equation 5.21 will be used to infer general predictions on the bond interface crystallization state – a property which is influenced by the cooling rate (Figure 6.6, p. 108). Values for P_L and $\dot{q}_0$ for different tape thicknesses d can be derived from Equation 5.1 or Figure 5.1 (p. 72).

5.8 Elastic Modulus within the Tape

Elastizitätsmodul im Tape

The previous sections presented how the changing temperature gradient influences the parameters melt pool depth, melt dwell time and cooling rate. Yet another factor was identified that is influenced by the temperature gradient, which might have been neglected in the literature: the *elastic modulus* within the tape and substrate's ground.

For common process speeds < 500 mm/s the thermal penetration in the tape is rather high (Figure 5.2). In general, the more a composite body is soaked by heat, the more elastic it becomes, and consequently easier formable (drapable). This is well known from composite sheet forming with higher material thicknesses of 0.2 to 4 mm [BENK14] [KUGE16]. It will be predicted how the temperature gradient influences this aspect in tape placement. By use of the temperature-dependent *flexural* modulus $E_{f_{tape}}(T)$ of PEEK/CF, the elastic modulus through the thickness can be obtained:

$$E(z, T) = E_f[T(z)] \quad (5.22)$$

Material Data. The transversal flexural modulus at room temperature of the tape is taken from [TENC17, p. 1]; the temperature-dependent flexural modulus of PEEK was taken from [SOLV16, p. 24]. The respective model of $E_f(T)$ is described in the Appendix, Section 19.2, p. 193.

Using the final temperature distributions $T(z)$ of Figure 5.2 (Equation 4.16 and 4.13) with the temperature-dependent flexural modulus model $E_f(T)$ yields the elastic modulus along the through-thickness direction z for various process speeds:

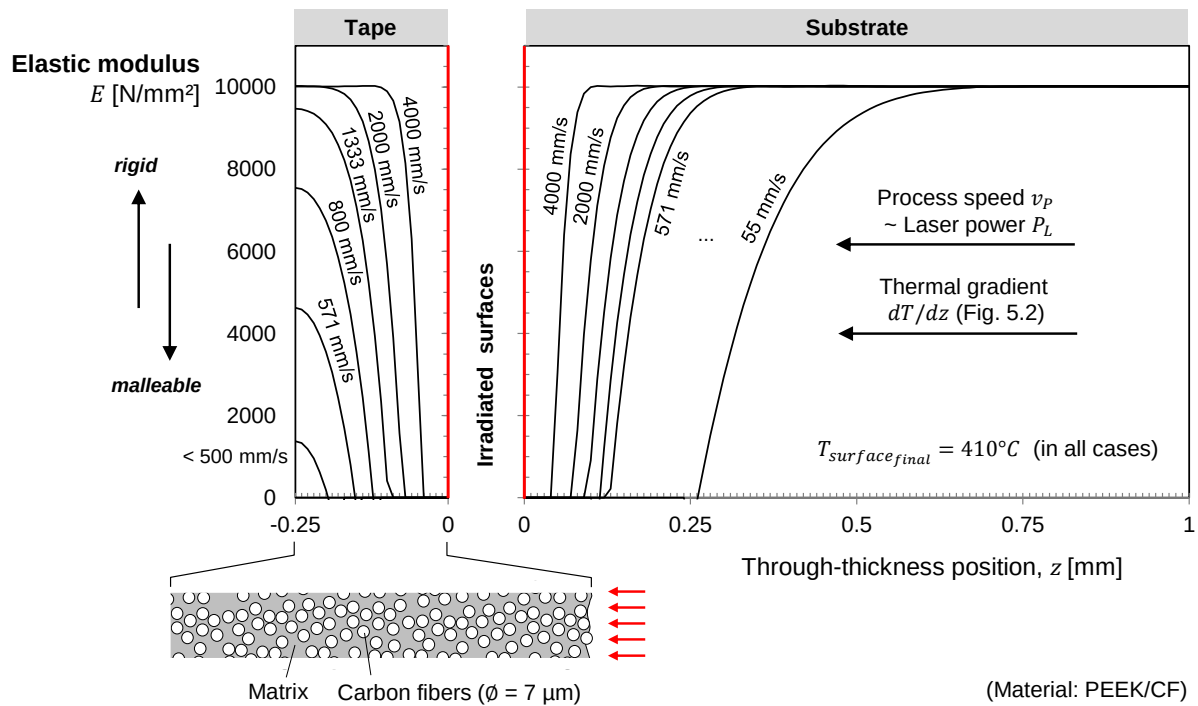


Figure 5.16: Elastic modulus in through-thickness direction within a tape, for different temperature gradients; please consider in combination with Figure 5.2. Higher speeds and laser powers make the tape increasingly rigid.

Elastizitätsmodul in Dickenrichtung bei verschiedenen thermische Gradienten; bitte betrachten Sie zusammen mit Abb. 5.2. Hohe Prozessgeschwindigkeiten und Laserleistungen versteifen das Tape.

For the 0.25 mm-thick tape, it can be observed that the elasticity becomes significantly influenced at speeds > 500 mm/s. The substrate ground undergoes a continuous change of the through-thickness elasticity. In general, both bodies become more rigid.

Resulting Consequences. The changing rigidity leads to:

- (a) An increasing *flexural modulus* in *width* and *fiber direction* of the tape
- (b) Retardation of *shear straining* in *through-thickness direction* of the tape

These mechanical aspects might impede the elastic roller from pressuring of the tape homogeneously onto the (mostly curved) substrate surfaces. Gaps/overlaps and surface waviness are common features of tape-laid structures. In general, the macroscopic surface roughness increases with more laid layers [LAMB04]. More on the impact of this phenomenon will be discussed in the following chapter.

6 Impact of the Thermal Skin Effect on the Placement Process

Wirkung des thermischen Skineffekts auf den Ablegeprozess

Previous chapters revealed a significant influence of the process speed on the through-thickness temperature distribution – thermal skin effect – and consequently an impact on the melt pool conditions. The question arises how these changing conditions influence the placement process, especially the weld strength: $\tau_{weld} \stackrel{?}{=} f[T(z, t)]$. The question will be addressed via theoretical analysis and experiments thereafter.

6.1 Interpretation of the Results for High-Speed Tape Placement

Interpretation der Ergebnisse für das Hochgeschwindigkeits-Tapelegen

In order to set the foundation for discussion, a comprehensive overview of the known mechanisms during tape placement will be presented (review). For the first time, these mechanisms will be analyzed on their sensitivity to temperature gradients. Figure 6.1 shows an overview of the known mechanisms at their respective *scales*. The analytical investigation will move from top to bottom, beginning with the plastic deformation. PEEK/CF will be used again as representative material, because of (a) the available data in the literature; (b) to evaluate the results from the transient thermal analyses.

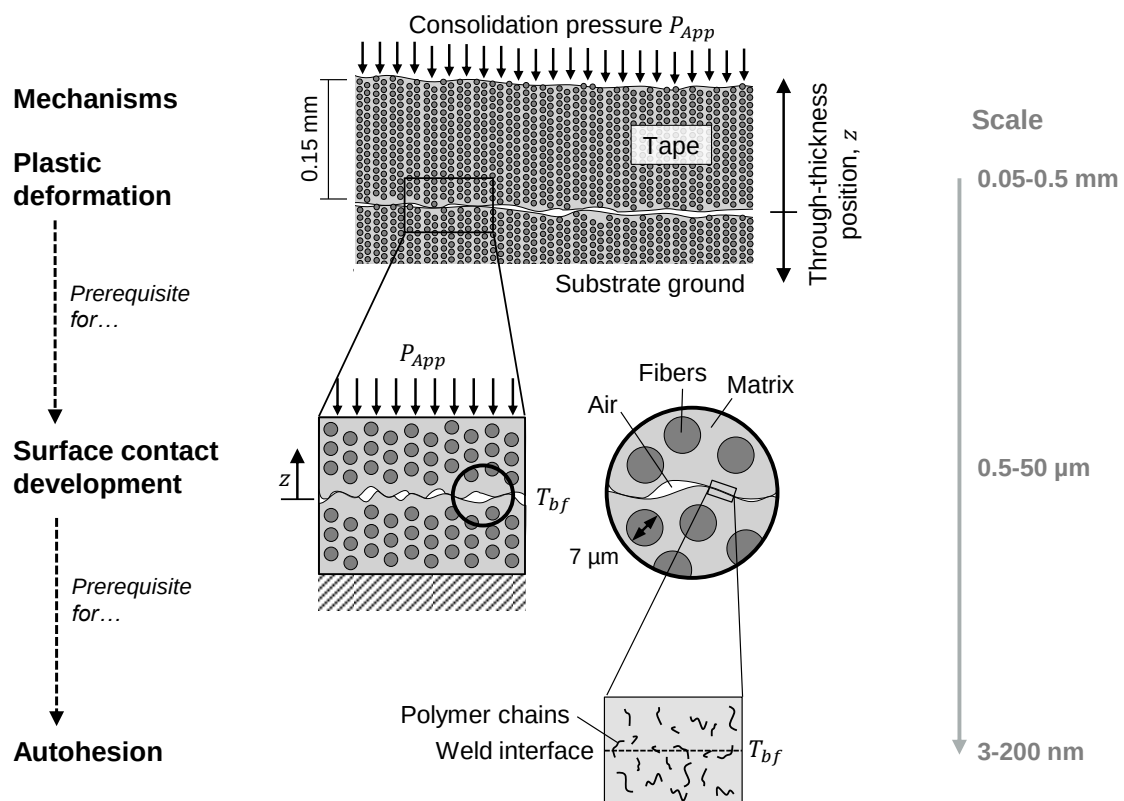


Figure 6.1: Mechanisms at different scales to be investigated on the influence of changing temperature gradients at higher process speeds

Mechanismen auf verschiedenen Größenordnungen zur Einflussanalyse der Temperaturgradienten bei hohen Prozessgeschwindigkeiten

6.1.1 Effect on the Tape Plasticity

Wirkung auf die Plastizität des Tapes

Thermoplastic tape placement is a three-dimensional process. During the laydown process, the tape undergoes various kinds of plastic deformation:

- *Bending and through-thickness shear straining* to conform to curvatures [DUBR15, p. 50], gaps/overlaps [STEY13, p. 96] and tape crossovers [COGS92, p. 131] on a comparatively macroscopic level ($> 50 \mu\text{m}$)
- *Shear straining in fiber direction* for steering of the tape [ESCH01, p. 28, 32-36] [BERE02, p. 70-77] [KERM15, p. 98]
- *Compaction and transverse squeeze flow* of the polymer with consequent tape flattening and widening [STEY13, p. 97] and void reduction [KHAN10, p. 110]

Conforming to Surface Geometry. The aforementioned mechanisms can affect the weld strength insofar, as they support (or retard) a uniform pressure transfer from the roller through the tape to the bond interface during its laydown. The tape has to bend and shear internally, to conform the substrate's surface – unless a hypothetically ideal flat substrate is present. The draping process becomes most important during laydowns on highly curved and irregular surfaces. A negative-case scenario would be the draping of a thick and rigid tape, e.g. a 0.25 mm-thick PEEK/CF tape, over a strongly curved geometry in two dimensions of space, e.g. onto a sphere.

Investigations on the correlation of the through-thickness temperature gradient and tape drapability are missing so far. From analysis of the changing elastic modulus, Figure 5.16, it can be expected that with process speeds $> 1000 \text{ mm/s}$, the draping process becomes significantly affected by the increasing temperature gradients (Figure 5.2). The tape will become more rigid and resistant against the pressure of the roller – especially elastic rollers could be sensitive to by such a “tape stiffening effect”.

On the one hand, process speeds of $\gg 1000 \text{ mm/s}$ are only known (in *in-situ* thermoplastic tape placement) from *winding* processes on *symmetrical* tubes of low surface curvature, e.g. [AUTO17b]. For tape *laying* systems, 6-axis robots have been reported to be limited at 1.6 m/s, but only for *2-dimensional* molds, excluding acceleration and deceleration [DOBI16]. It therefore seems unlikely that increasing temperature gradients will become a significant issue for *3-d draping* very soon, because the available machine dynamics limit the fast draping of complex-shaped substrates.

On the other hand, composite parts can exhibit surface *waviness* and *ripples* in the range of $50 \mu\text{m}$ to 0.5 mm (peak-to-valley height). Those can emerge either by non-closed tape gaps in the laminate, tape crossovers or by tolerances in the tape thickness along its width. With more layers stacked, the surface waviness generally grows [LAMO02, p. 5-6]. Conforming to the surface waviness could be significantly affected by the temperature gradients, as lower heat soaks and thinner melt pools makes the tape less malleable and melt flow more inhibited. Higher heat soaks could be beneficial for the closing of gaps during tube winding and overwrapping in general.

Gap-and-Overlap-Free Tape Laydown. The manufacturing of laminates with narrow gaps and no overlaps is an important task for process optimization, because those affect the mechanical properties of the final product as well as its optical appearance [LAMO02, p. 5-6] [STEY13, p. 103]. In this context, STEYER investigated the effect of tape *flattening/widening*. Investigations found that 12 mm-wide tapes of 0.15 mm thickness could widen by a factor of 200% to 24 mm and flatten out to 0.075 mm. The author modelled the phenomenon and mentioned that for an accurate prediction of the widening process, the through-thickness temperature distribution should be considered [STEY13, p. 97], but was finally not included in the model.

From analysis of the elastic modulus in Section 5.5, it can be concluded that the observation of STEYER becomes especially relevant when the process speed exceeds 500 mm/s. At 1000 mm/s, half of the tape's elasticity is affected. A prevention of the "tape widening effect" can therefore only occur at very high process speeds, at least for the investigated PEEK/CF tapes of 0.25 mm thickness. A continuous decline of the tape widening effect with increasing process speeds is expected.

Surface Appearance. The surface appearance of a laminate is significantly influenced by the aforementioned avoidance of gaps and overlaps [STEY13, p. 103]. Practical investigations have also shown that the roller surface imprints on the backside of the tape [STEY13, p. 66]. This effect will certainly be influenced by the aggregate state at the tape backside (molten/solid). Steep temperature gradients leave the backside in solid state and therefore more resistive against deformation. It can be expected that high-gradient processes generally lead to smoother laminate surfaces – given that the tape itself is flat in the first place (more on this effect in Subsection 6.2.4)

Interim Conclusion. With higher process speeds, the temperature distribution within the material undergoes a significant shift, from highly soaked to narrowly molten, until only the foremost micrometers of the surface are molten (Figure 5.13). The subjacent material remains solid (and therefore rigid). At some magnitude, this shift will certainly begin to influence the formability of the tape. However, no definite statement can be made yet at which point this will happen. Section 6.2 will therefore propose a novel experimental setup to investigate the issue under controlled conditions.

Regarding tape plasticity, the maximum allowable temperature gradient will strongly depend on the specific attributes of the tape and substrate (flatness, thickness, polymer viscosity, fiber distribution). Comprehensive overviews of tape *characteristics* are given in [JENS12] [MACK14] and [SCHA15]. It can still be hypothesized that flat temperature gradients (/ high heat soaks) are generally beneficial for:

- 3-d substrates of high curvature and
- high surface waviness/ripples (gaps/overlaps, tape crossovers), to support the draping of the tape via a lower through-thickness plasticity.

Vice versa, strong temperature gradients (/ low heat soaks) are beneficial for:

- 2-d and 2.5-d substrates of high flatness (low surface waviness /ripples) and
- in case tape flattening should be avoided for gap-/overlap-free path planning.

6.1.2 Effect on the Development of Intimate Surface Contact

Wirkung auf die Ausbildung des intimen Flächenkontakts

The reliable development of an *intimate surface contact* is one of the key technological challenges for in-situ thermoplastic tape placement. In general, intimate contact among polymers is the consequence of pressure and time at reduced surface viscosity. Therefore, a fast-propagating contact development requires $T_{surfaces} > T_{melting}$. During the process, a flattening of the surface asperities and a merging of the melt pools into one uniform bond layer takes place (middle of Figure 4.1, p. 48).

Models. The process has been modelled by several previous authors. An overview of models is already given in [AGEO02, p. 106]. The simplest model of DARA & LOOS includes the *viscoelastic deformation* of the surface asperities and the parameters pressure, temperature and time [DARA85]. The model was extended in the succeeding years by LEE & SPRINGER [LEE87a], MANTELL & SPRINGER [MANT92a, MANT92b], SONMEZ & HAHN [SONM97a] as well as YANG & PITCHUMANI [YANG01a, YANG01b]. The model of YANG & PITCHUMANI distinguishes itself by the use of *fractals* for the mathematical description of the surface roughness from measurement data.

SCHAEFER et al. investigated the surface contact development process of carbon-fiber-reinforced Polyamide-6 tapes (PA 6). The authors compared different models with experimental results on the prediction accuracy. It was found that the used models – originally derived for PEEK/CF – overestimate the required time to complete a full surface contact, due to the different viscosity of PA 6 and a resin-rich surface. [SCHA17, p. 595] It must also be noticed that all previous models were derived from *homogeneous pressuring* of *flat* specimens; the positive effects of roller-based consolidation with *shorter void squeeze-out distance* was not considered yet.

Approach. The specifics of the models will not be the topic in this thesis. Instead, the often-cited model of MANTELL & SPRINGER (Equation 6.1) will be used to analyze the effect of temperature gradients. The common term used in modelling is the *degree of intimate surface contact* D_{IC} . It is defined as the fraction of *actual* surface contact after some elapsed time t and the *maximum achievable* surface contact [MANT92a]:

$$D_{IC}(t) = \frac{\text{surface contact at time } t}{\text{max. surface contact}} \approx R^* \left[\int_0^t \frac{P_{App}}{\mu_0(T)} dt \right]^{1/5}; \quad 0 < D_{IC} < 1 \quad (6.1)$$

where P_{App} is the magnitude of the consolidation pressure, $\mu_0(T)$ the temperature-dependent (zero-shear rate) viscosity of the polymer and R^* a “lumped” proportional coefficient to describe the influence of the surface roughness.

$\mu_0(T)$ has been modelled by several authors, both for a PEEK/CF *mixture* as well as for *neat* PEEK. A comparative summary of models was presented in [STOK16a, p. 21]. For resin-rich surface layers, the values of neat PEEK can be used [TIER06, p. 1495]. If no polymer layer is present, the values for a PEEK/CF mixture are the more conservative consideration. In the following, a resin-rich layer we will assumed.

It has to be noted that the viscosity models $\mu_0(T)$ vary considerably by several decimal powers (revised in Figure 20.1, p. 198). Figure 6.2 reveals therefore only the *general* effect of pressuring time, viscosity (and thereby temperature) on the required time to achieve a complete intimate surface contact, $D_{IC} = 1$. The computation also assumes *isothermal* and *isobaric* conditions (*static* temperature and pressure). The plot shows the positive effect of long, elevated temperatures during applied pressure. Please notice that during tape placement, the viscosity (and pressure) change over time, when the melt cools out after the heating phase (Figure 5.3, p. 74).

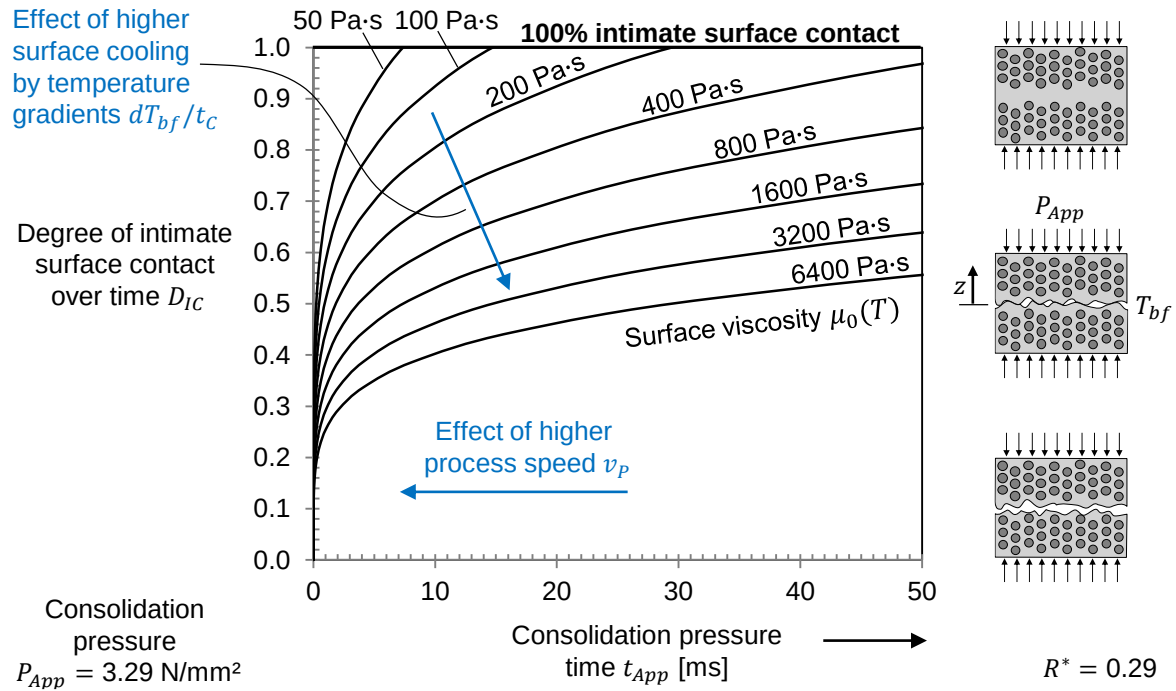


Figure 6.2: Degree of intimate surface contact among PEEK/CF tapes as a function of pressuring time and viscosity assuming isothermal and isobaric conditions.

Grad des intimen Flächenkontakts zwischen PEEK/CF-Tapes als Funktion der Druckzeit und Viskosität unter Annahme isothermer und isobarer Bedingungen.

The parameter R^* is an empirical “lumped” coefficient to describe the influence of surface roughness. It was derived empirically. MANTELL et al. determined the value to 0.29 for a typical PEEK/CF tape [MANT92b, p. 2385]; LEE & SPRINGER to 0.45 [LEE92, p. 1052]. It is likely that R^* varies in modern tapes. Especially resin-rich surface layers offer surface roughness of $R_z < 5 \mu\text{m}$ (compare Figure 18.2, p. 188).

The process of intimate surface contact development can be regarded as highly specific for each tape product. Independent from the specifics of the tape, the following processing parameters support a *reliable* development of intimate surface contact:

- Level and residence time of high temperatures in the bond interface $[T_{bf} \cdot t]$ for minimized viscosity $\mu_0(T)$ during the pressure duration t_{App}
- Magnitude and exposure time of consolidation pressure $[P_{App} \cdot t_{App}]$

Figure 6.2 shows why *static post-consolidation* methods, like the radiation-induced vacuum consolidation process, presented in Section 1.3 (p. 7), are able to achieve high

consolidation qualities, due to the long and controlled *isothermal* and *isobaric* processing. Regarding the tape design, the following aspects are beneficial:

- Low surface roughness or high surface flatness (factor R^*)
- Low zero-shear rate viscosity μ_0

Effect of Increasing Process Speeds. In Section 5.5 and 5.6 it was observed that with increasing process speeds, the melt dwell time t_{melt} decreases and the bond interface cooling rate dT_{bf}/dt_c increases. Simultaneously, the exposure time of the consolidation pressure t_{App} decreases with $1/v_P$ [MANT92a, p. 2363], because:

$$t_{App} = \frac{x_{App}}{v_P}; \quad x_{App} = f(E_R, d_R) \quad (6.2)$$

The absolute pressuring time t_{App} depends on the system-specific roller attributes, like elasticity E_R and diameter d_R . The substrate curvature can mostly be neglected, unless it is significantly stronger curvature than the roller. The determined roller contact length x_{App} varies in the literature from < 1 mm for rigid rollers ($d_R = 10$ -70 mm) up to 28 mm for elastic rollers ($d_R = 80$ mm) [SONM97b, p. 405] [STOK14, p. 107].

Effect of Melt Pool Thinning. No research work is known on the effect of the melt depth. The melt depth was found to decrease continuously with higher speeds (Figure 5.13); the decline is illustrated in Figure 5.4. From comparison with other thermoplastic bonding processes, like laser transmission welding or pipe welding, it is likely that this “melt thinning effect” does impede the intimate surface contact development as well.

Case Analysis. Processing at 2000 mm/s with a pressure length x_{App} of 28 mm leads to a pressuring time t_{App} of 14 ms (Figure 6.2). This would require the surface PEEK melt to be at < 100 Pa·s during pressuring, which in turn would require the bond interface to remain at 550°C (according to the model of KHAN et al. Figure 20.1, p. 198), assuming isothermal and isobaric conditions. The melt pool is only 10-20 μ m deep (1-3 carbon fiber diameters). For these reasons, 2000 mm/s appears to be a quality-critical case. Increasing the process speed would require extended pressuring lengths, longer elevated bond interface temperatures and therefore higher thermal penetration. Both conditions are not possible to induce with conventional technologies (Figure 5.5).

Identified Limitations. It therefore follows that the aforementioned correlations lead to an inherent speed limitation for in-situ consolidation (Figure 6.4) – either by a decreasing pressuring time or by the identified decreasing melt dwell time. Tapes with low surface roughness and low melt viscosity will be less affected. Notice that the process speed limit will not occur in form of a fixed value, but rather as a *continuous decline* of the weld strength, similar to what has been observed in [AUGU14b], p. 38.

It is currently uncertain, at which process speed the temperature gradient significantly prevents the development of intimate surface contact, due to the complexity of each specific case. Section 6.2 will therefore propose a novel experiment to investigate the bonding of tapes at different temperature gradients and defined consolidation speeds.

6.1.3 Effect on Autohesion

Wirkung auf die AutohäSION

Autohesion is the interdiffusion of polymer chains across the bond interface and critical for the weld strength development. The process requires polymers to be heated and in contact for a certain period of time. Pressure was found to have *no direct* effect on autohesion [LEE87a, p. 1039], besides the required (pressure-dependent) surface contact development (Figure 6.1). A review on autohesion was presented in [AWAJ16].

The (time-dependent) *degree of autohesion* $D_{Ah}(t)$ is defined by the ratio of the bond strength after some elapsed time t and the maximum achievable bond strength:

$$D_{Ah}(t) = \frac{\text{bond strength at time } t}{\text{max. bond strength } (t \rightarrow \infty)} = \left[\int_0^t \frac{1}{t_w(T)} dt \right]^{1/4}; \quad 0 < D_{Ah} < 1 \quad (6.3)$$

$t_w(T)$ is the temperature-dependent reptation/welding time and is specific for each polymer. For PEEK, various models have been presented and were recently reviewed in [STOK16a, p. 21]. It was found that the models of $t_w(T)$ differ significantly. An overview of two models is given in Section 20.1 and shown in the following figure:

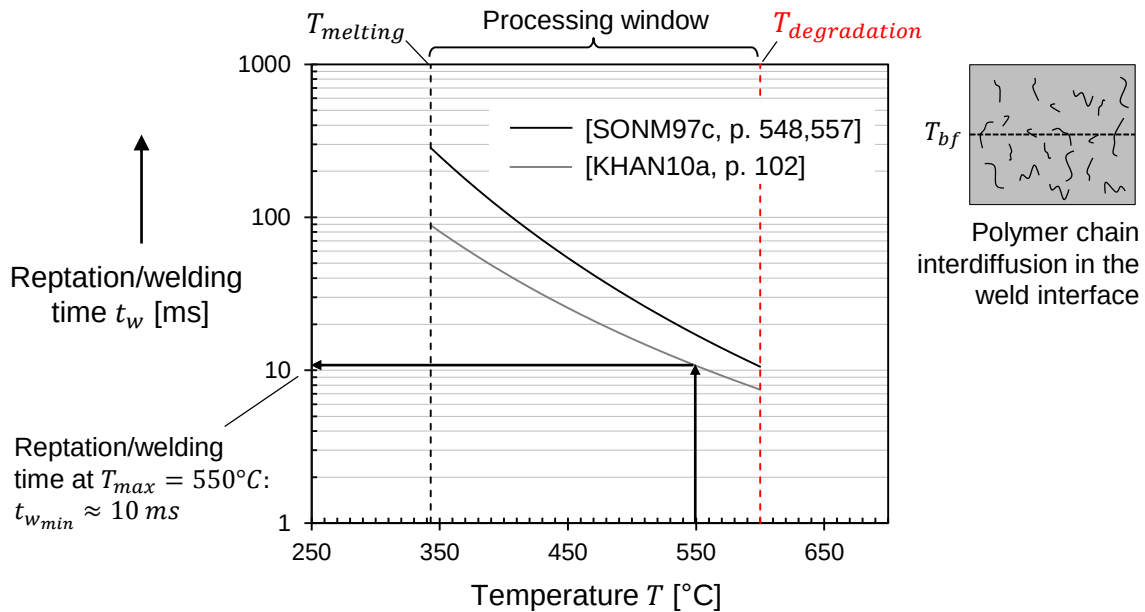


Figure 6.3: Reptation/Welding time as a function of temperature for PEEK

Reptations-/Fügeschweißzeit als Funktion der Temperatur für PEEK

All $t_w(T)$ models have in common that with decreasing temperature, the required time to complete autohesion increases with $e^{1/T}$, from a minimum of 10 ms at 560 °C up to 92 ms at 350 °C, in case of the model by KHAN et al. (Figure 6.3).

In Subsection 5.1.1 it was shown that with increasing process speeds, the bond interface cooling rate decreases continuously with $\approx 1/v_p$, from 45 °C/ 20 ms for 55 mm/s, up to 266 °C/ 20 ms for 4000 mm/s (Figure 5.3). As for the case of surface contact development, (conventional) tape placement machines (with fixed irradiation) are therefore limited in terms of process speed when the interface-cooling rate surpasses the necessary magnitude of temperature/time for autohesion to complete.

6.1.4 Effect on Weld Strength Formation

Wirkung auf die Ausbildung der Fugeschweißfestigkeit

As mentioned in the previous section, autohesion can only proceed when the surface asperities have flattened out and reached a high degree of intimate contact D_{IC} . Therefore, the ultimate bond strength (*degree of bonding* D_B) is defined by:

$$D_B = D_{IC} \cdot D_{Ah} \quad (6.4)$$

In the time domain, the progression of $D_B(t)$ depends on the progression of $D_{IC}(t)$ and $D_{Ah}(t)$. YANG & PITCHUMANI realized this correlation and introduced a model that coupled both mechanisms, $D_{Ah}(t)$ and $D_{IC}(t)$, in the time domain [YANG03, p. 269]:

$$D_B(t) = D_{IC}(0) \cdot D_{Ah}(t_f) + \int_0^{t_f} D_{Ah}(t_f - t) \frac{dD_{IC}}{dt} dt \quad (6.5)$$

with t_f being the final time. GROUVE found in studies on PPS/CF that the intimate surface contact takes 2 decimal powers more time to develop than autohesion [GROU12, p. 82]. Therefore, $D_{IC}(t)$ appears to be the “bottleneck” process for high-speed processing of tapes. In any case, the dependency of $D_{Ah}(t)$ on $D_{IC}(t)$ makes the process more sensitive towards high temperature gradients.

The strength of the weld can further be influenced by secondary effects, like the state of crystallinity (next subsection) and local thermal stresses, however most authors have stressed the importance of the degree of bonding D_B for the final weld strength.

Interim Conclusion. In view of the thermal analyses from previous sections, it can be concluded that the weld strength will at some point (inevitably) be influenced by the process speed, due to the continuously increasing temperature gradients. The question of whether intimate contact development is the imitating factor – or other mechanisms like formability, macro melt flow or crystallinity – depends highly on the specific properties of the tape, machine and workpiece.

Hypothesis for Declining Weld Strengths at Increasing Process Speeds in Laser-Assisted Thermoplastic Tape Placement

The previous findings can be summarized in an explanatory model, Figure 6.4, next page. The model depicts the identified correlations and influencing factors. It predicts a declining weld strength τ_{weld} in tape-placed structures with laser-assisted tape placement systems, caused by three major factors: (1) decreasing pressuring time x_{App} (2) increasing cooling rate dT_{bf}/dt_c (decreasing melt dwell time t_{melt}) and (3) thinning melt pool depth δ_{melt} . With higher speeds, the quality of the weld strength becomes more *sensitive* towards the tape/substrate properties and machine attributes.

Design Recommendations. From the model, several recommendations can be derived for the design of high-speed placement machines and the design of fast-processable tapes: First of all, high-speed machines should enable high and elongated consolidation pressures: $P_{App} \uparrow, t_{App} \uparrow$.

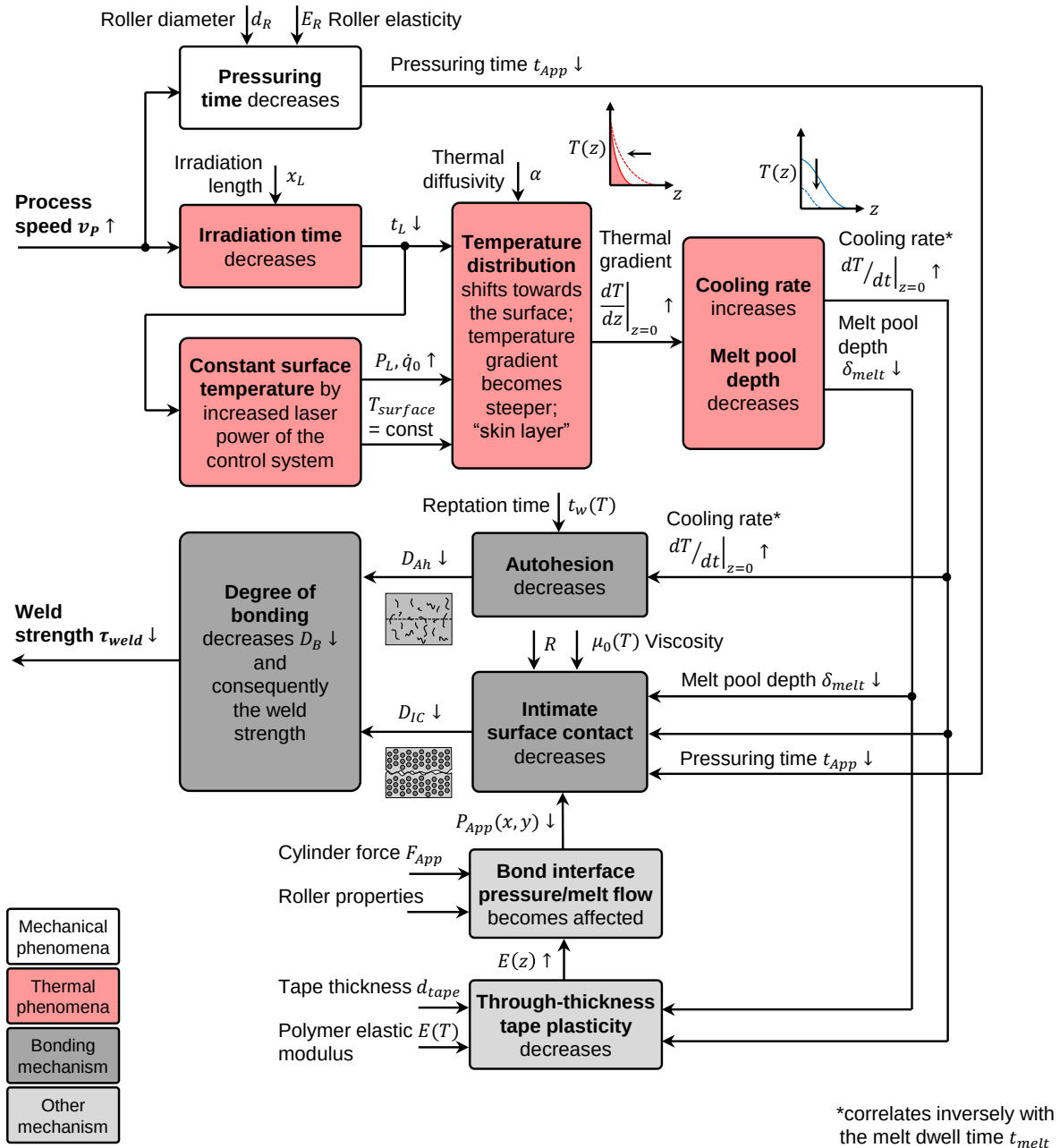


Figure 6.4: Explanatory model for the continuous decline of the weld strength at increasing process speeds (laser power is not limited in the consideration)

Erklärungsmodell zur kontinuierlich abnehmender Fügefestigkeiten bei zunehmenden Prozessgeschwindigkeiten (Laserleistung ist nicht begrenzt)

The roller diameter and its elasticity should therefore be maximized $d_R \uparrow, E_R \uparrow$; under consideration of durability and laser shading. Secondly, the laser should enable adjustable irradiation in material feed direction $I_L(x)$, to control the thermal penetration δ_{therm} and thereby the cooling rate dT_{bf}/dt_c and melt pool conditions $\delta_{melt}, t_{melt}, x_{melt}$ (Chapter 7). The tape should feature a resin-rich and smooth $R^* \downarrow$ surface polymer layer of low (zero-shear rate) viscosity at the processing temperature $\mu_0 \downarrow$ and a high thermal diffusivity $\alpha \uparrow$, under the boundary conditions of the required mechanical properties in the final product. Polymer cost per composite volume must be considered as well – especially in combination with low-cost fibers, e.g. glass fibers with $\approx 1 \text{ €/kg}$.

6.1.5 Effect on Reconsolidation and Post Healing

Wirkung auf die Nachkonsolidierung und Ausheilung

In the works of KHAN et al. and MANTELL & SPRINGER it was found that after *repetitive passes* of the consolidation system, subjacent layers were further “re-“consolidated [MANT92a] [KHAN10b, p. 8-9] [KHAN12, P. 488]. In this context, STIMPFL identified a decreasing weld strengths in the outer layers of wound tubes [STIM14, p.108].

KHAN et al. states that 3 additional passes on the upmost layer are necessary to fully reconsolidate the outer layers. More additional passes do not improve the consolidation [KHAN09b, p. 7]. MANTELL & SPRINGER found that at least 5 additional passes are necessary to reach maximum intimate surface contact [MANT92b, p. 2400]. In a prior analysis, the authors already proposed to include multiple passes in models of intimate surface contact development D_{IC} [MANT92a, p. 2367].

Effect of Increasing Process Speeds. The “reconsolidation effect” diminishes the necessity to achieve high intimate contact and autohesion at the first laydown. The effect of inter-layer contact resistances, discovered by LEVY et al. [LEVY14], might *intrinsically* supports repetitive consolidation, because a poor consolidation leads to a heat flow barrier R and thereby to heat accumulation in subjacent interfaces during repetitive passings (compare Figure 4.9, p. 64) – a *self-compensating* process cycle.

Processing of thin tapes supports repetitive consolidation and healing because heat can reach previous bond interfaces more easily. However, a critical prerequisite for repetitive consolidation/healing is a *sufficient thermal penetration* δ_{therm} – independent from the specific material conditions (please compare Figure 5.2 and Figure 5.3). Strong temperature gradients in through-thickness direction z and thick tapes will inhibit this effect from occurring, because only the foremost area of the substrate tends to become heated under such conditions (“skin layer effect”). If the interface asperities are not consolidated further, additional healing is also inhibited, as it can only proceed in areas of intimate surface contact [STOK15a, p. 281].

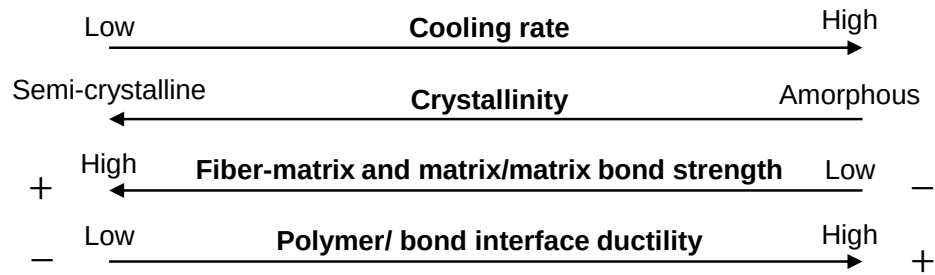
6.1.6 Effect on the Crystallinity in the Bond Interface

Wirkung auf die Kristallinität in der Fügefläche

During the placement process, areas of the composites polymer undergo a phase change from solid to molten during heating and back to solid again, during cooling. In semi-crystalline polymers, like PEEK, the crystallinity of the workpiece develops in multiple heating/cooling cycles over the part’s manufacturing history [SONM97a].

The state of crystallinity determines several mechanical properties of the part; with conflicting aspects: Whereas the strength of the *fiber-matrix* and *matrix-matrix bond* increases with higher crystallinity, the *ductility* of the polymer decreases (Figure 6.5). The resulting *fracture toughness* of the laminate is therefore a complex interaction of those two aspects. [GAO00b, p. 773]

Several recent works on tape placement have found a positive correlation between low crystallinity (amorphous state) and fracture toughness for PEEK/CF [LEE87b, p. 10] [GAO00b, p. 765]. In this context, GROUVE identified an increased fracture toughness by a factor of 2 for laser-tape-placed PPS/CF specimens (with high cooling rates) compared to *annealed* specimens [GROU12, p. 101]. Most authors attribute the higher fracture toughness to the higher ductility of the polymer at low degrees of crystallinity:



" + ": positive aspect

Figure 6.5: Conflicting aspects of the matrix crystallinity in composites

Gegensätzlich Aspekte der Matrix-Kristallinität in Faserverbundkunststoffen

The state of crystallinity results from the cumulative time the polymer undergoes the crystallization window [STOK15a, p. 280] (from 190 to 280°C for PEEK, [TARD14]). A research summary on the correlation between cooling rate and crystallinity is given in [GAO00a, p. 521]. The correlation is revised in Figure 6.6 (black bolded curve).

Crystallinity in Bond Interface. Instead of addressing the crystallinity of the whole *workpiece*, like in [SONM97a] and [GUAN04], the focus of research shifted recently to the *bond interface* crystallinity. This is because high-power lasers enable more local heating with consequently higher cooling rates near the bond interface at speeds > 100 mm/s. The topic has been addressed by GROUVE for the case of PPS/CF and STOKES-GRIFFIN & COMPSTON for PEEK/CF [GROU12, p. 102-110] [STOK15a, p. 280-281]. GROUVE states that the high local cooling rates (in laser-assisted tape placement) – typically at > 400°C/s – mainly determine the crystallinity of the bond interface. He showed that the prevailing cooling rates cause the bond interface to remain amorphous and therefore ductile. After annealing of the bond interface, the fracture toughness *decreased* again [GROU12, p. 106]. The analysis however ignored intrinsic annealing by subsequent passes.

Intrinsic Annealing. STOKES-GRIFFIN & COMPSTON found that subjacent bond interfaces still undergo significant annealing at placement rates of 100 mm/s, because the interfaces will be reheated above 190°C during subsequent passes. This statement can be confirmed by the predicted through-thickness temperature distributions for various process speeds in Figure 5.2. The situation remains as described until process speeds of 400 mm/s are exceeded [STOK15a, p. 281] (please compare Figure 5.2 again).

Effect of Increasing Process Speeds. From results of the transient thermal analyses in previous subsections, it can be concluded that the bond interface crystallinity will proceed to decline with higher process speeds, due to increasing (local) cooling rates, caused by the increasing temperature gradients.

Figure 6.6 depicts the identified cooling rates at increasing process speeds of Chapter 5 (p. 74, p. 78) within the known crystallinity-cooling-rate graph of PEEK. The crystallinity data from 1 to 1000°C/s is based on data given in [GAO00a, p. 521]; the data > 1000°C/s is taken from [LEE87a, p. 1055].

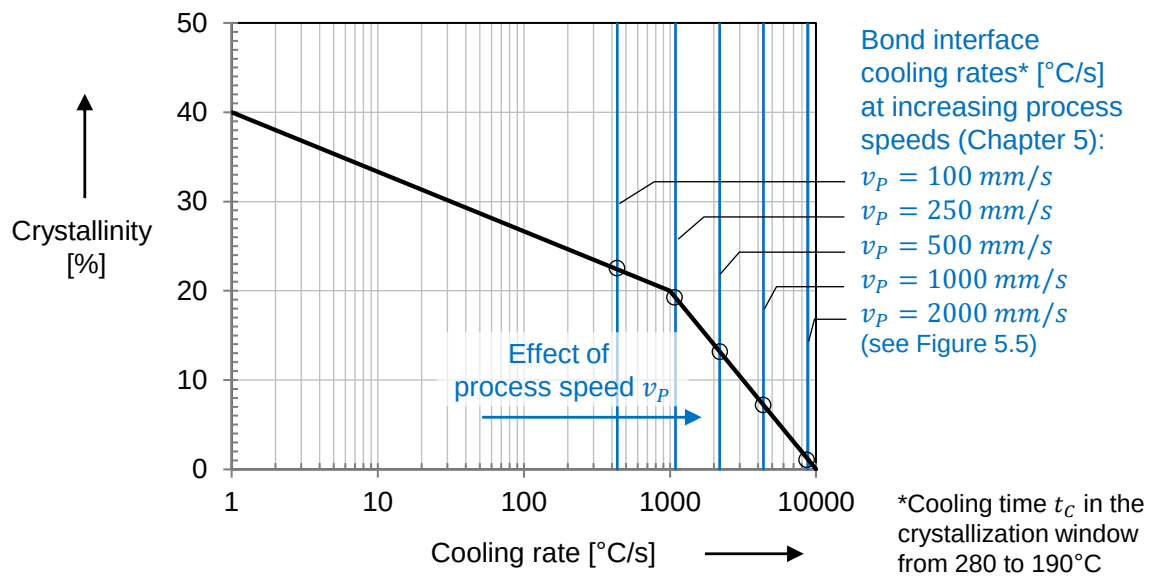


Figure 6.6: Crystallinity of neat PEEK resin in comparison to the determined cooling rates in the bond interface at different process speeds

Kristallinität von reinem PEEK im Vergleich zu den ermittelten Abkühlraten in der Fügezone verschiedener Prozessgeschwindigkeiten

The results of Chapter 5 therefore reinforce the statements of previous authors on bond interface cooling rates of > 400°C/s in laser-assisted tape placement. It can be observed how with increasing speeds, the bond interface crystallinity declines. Process speeds of > 1000 mm/s should lead to a crystallinity of < 10%.

Limit of Intrinsic Annealing. Multiple passes of the consolidation system can still increase the crystallinity in subjacent bond interfaces, as previous layers undergo additional heating cycles. However, this effect can only occur up to the point when previous bond interfaces remain < 190°C (below the recrystallization temperature for PEEK), due to the declining thermal penetration. The analysis in Subsection 5.1.1 showed that this will occur at 500 mm/s (assuming a 0.15-mm thick tape and the workpiece to cool down to T_0 again until subsequent placement processes; increasing $T_{surface\,final}$ increases the thermal penetration). With process speeds > 500 mm/s, the bond interface fracture toughness is expected to increase, due to the lower levels of crystallinity (higher ductility), while the (crystallinity-related) strength will decrease.

6.1.7 Further Secondary Effects

Weitere Sekundäreffekte

Effect on the Surface Temperature Drop in the Laser-Shading Zone

In all roller-based laser-assisted tape placement systems, a certain distance of laser *shading* is present, where the surface heat flux declines to zero [KOEL08, p. 40] [STEY13, p. 39] [WEIL16b, p. 11]. During passage of this zone, the surface temperature drops by a certain degree, depending on the specific system design (roller diameter, laser bias angle, material reflectance) [STOK14, p. 113] [STOK15b, p. 1456].

Therefore, the surface polymer has to be heated above the targeted nip point temperature before entering the shading zone. The phenomenon narrows the processing window of a respective polymer. Shading was not modelled in this thesis, due to the aim of generating general, rather than system-specific knowledge. Nonetheless, general statements can be made whether high process speeds (/ high temperature gradients) affect the requirements for overheating:

On the one hand, increasing temperature gradients lead to increasing cooling rates (Section 5.5, p. 92). It was shown that the melt dwell time t_{melt} decreases with $\approx 1/v_p$ (Equation 5.18 and Equation 5.19). This effect on its own would require more overheating to compensate a more rapid temperature drop in the shading zone. However, at the same time, higher process speeds lead to shorter passing times through the shading zone – higher mass flow –, at a similar rate of $1/v_p$. It therefore appears that the two effects cancel each other out. More research work into this topic is required.

Void Reduction and Post Impregnation

Semi-impregnated (and poorly impregnated) tapes possess voids throughout their thickness. Processing of such materials does not only require consolidation of the tape interfaces, but also further impregnation and void reduction within the tape itself during the laydown. Complete impregnation and void reduction was found to be only possible by multiple passes of the consolidation system [KHAN10b, p. 6-9]. Such a post impregnation process clearly requires the tape to be heated throughout its thickness.

Void-free tapes can deconsolidate during the heating phase. This effect requires an internal reconsolidation at the laydown [KOK16, p. 5-8]. It is expected that the effect can be reduced by inducing high temperature gradients. This requires the processing with respectively high laser powers at high speeds (compare Figure 5.2).

Interim Conclusion. One can conclude that weak temperature gradients are generally positive for semi-impregnated (or poorly impregnated) tapes, to support void reduction and post impregnation. Vice versa, strong temperature gradients are positive for tapes of high impregnation quality to avoid tape deconsolidation in the heating phase.

6.2 Experimental Investigations

Experimentelle Untersuchungen

The previous sections analyzed how temperature gradients can (in principle) influence the laydown process and consequently the weld strength. In order to investigate at which process speeds such effects become significant for the bond interface, and to investigate the multitude of effects under controlled conditions, an appropriate experimental setup was required.

This section will present this setup, which will later be used for a first comparative analysis on the effect of temperature gradients for a specific tape. The analysis will focus on the weld strength at high process speeds, as these are the most critical optimization parameters in tape placement. A separate investigation of all previously mentioned effects was not possible yet.

6.2.1 Experimental Setup (Pull-Through Test)

Prüfstands Aufbau (Durchzugversuch)

The depicted setup in Figure 6.7 was devised to process tapes under controlled thermal through-thickness conditions. The setup pursues a symmetrical heating of two tapes in standstill position, with a controlled subsequent pull through a consolidation system, consisting of two opposing rollers. High acceleration rates were required to avoid inappropriate decays of the gradients, so to emulate real process conditions.

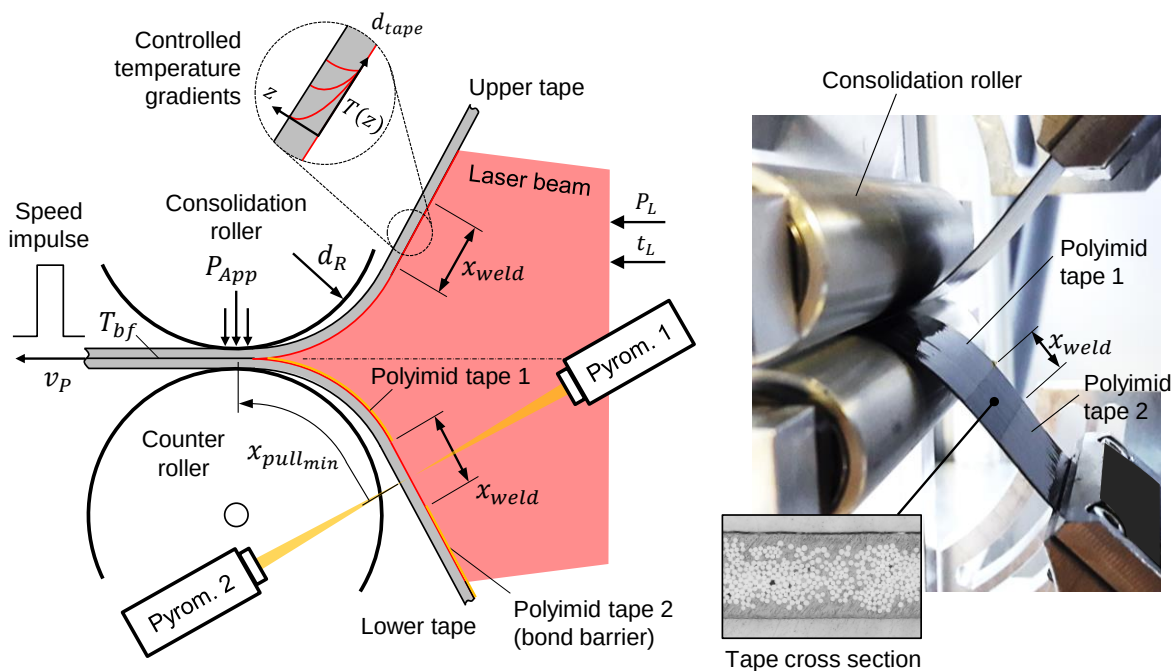


Figure 6.7: Principle (left) and magnified view (right) of the pull-through test with prepared probe for defined weld length (extended pictures in the Appendix, p. 178)

Prinzip (links) und Vergrößerung (rechts) des Durchzugversuchs mit präparierter Probe zur Isolation der Fügeschweißlänge (w. Bilder Anhang, S. 178)

The larger test setup is depicted in Figure 6.9 (next page), with the drive system and the testing procedure shown in the time domain. A magnification of the process area is shown in Figure 15.2 (p. 178); the process flow is depicted subsequently.

Comparison to State-of-the-Art Test Setups. A similar test setup, that uses the rewinding principle, has been presented by LATRILLE for the *continuous bonding* of tapes [LATR03, p. 68-69]. STOKES-GRIFFIN & COMPSTON used a conventional tape placement system of the company AFPT to investigate the effect of the placement rate [STOK15a, p. 276]. The *pull-through test* pursues a *discontinuous* bonding of tapes and is specifically devised for tape bonding under different temperature gradients.

Bonding Strategy. What is common with previous experiments is that the pull-through test reduces the tape placement process to the bonding of two single tapes. This procedure prevents the secondary effects of repetitive consolidation/healing (Chapter 6.1.5). The test neglects preheating, instead emulating a “cold” in-situ process. Further advantages on bonding of two tapes for research purposes are given in [STOK16a, p. 20]. It has to be pointed out that the effect of heat accumulation can be stronger in this method, because heat cannot flow out of the tape’s backside as it could do within a thicker cold substrate.

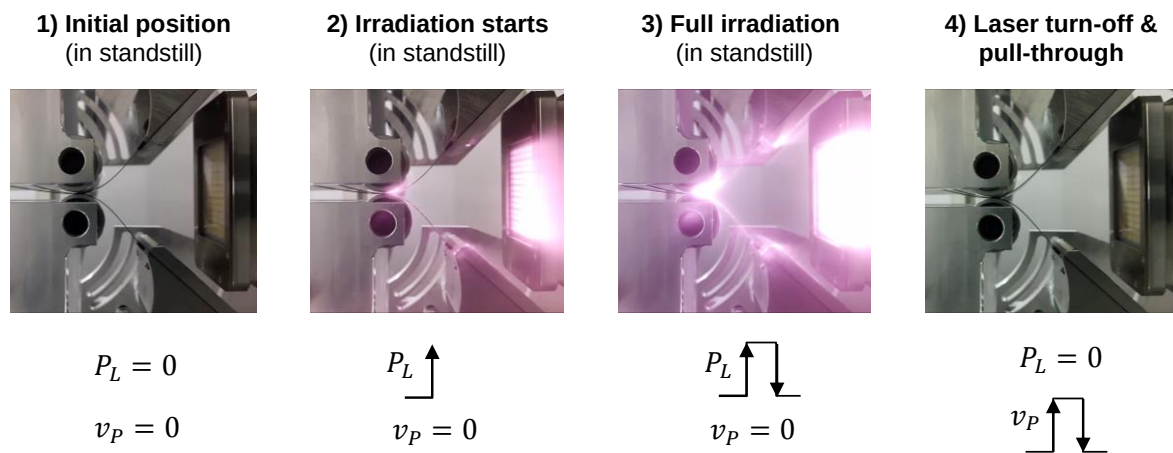


Figure 6.8: General process flow of the pull-through test

Prinzipieller Prozessablauf des Durchzugversuchs

Test Process Flow. At the beginning of the experiment, the laser begins to irradiate the two tapes symmetrically with a predefined combination of laser power P_L and irradiation time t_L (Position 1 to 3 in Figure 6.9). By this it was possible to induce defined temperature gradients. After reaching a predefined surface temperature, the tapes were pulled to (and through) the consolidation rollers at a predefined speed (Position 4 to 6). Exact timing of the laser flashing and motor start was critical, to reach the defined temperature gradients and surface temperatures at the nip point.

Defined Speed at the Nip Point. The tapes also had to be accelerated in such a way that they move in a defined (and constant) speed when reaching the nip point (Position 5). For this to ensure, a *loose bow* of tape with a certain length l_{bow} was introduced to decouple the spool acceleration from the tape pulling process (Figure 6.9, position 2 to 3). The spool is represented in the figure by the rotary inertia I_{rot} .

After reaching the desired rotational speed, the tape is pulled at near-constant linear speed (1 m/s in later trials).

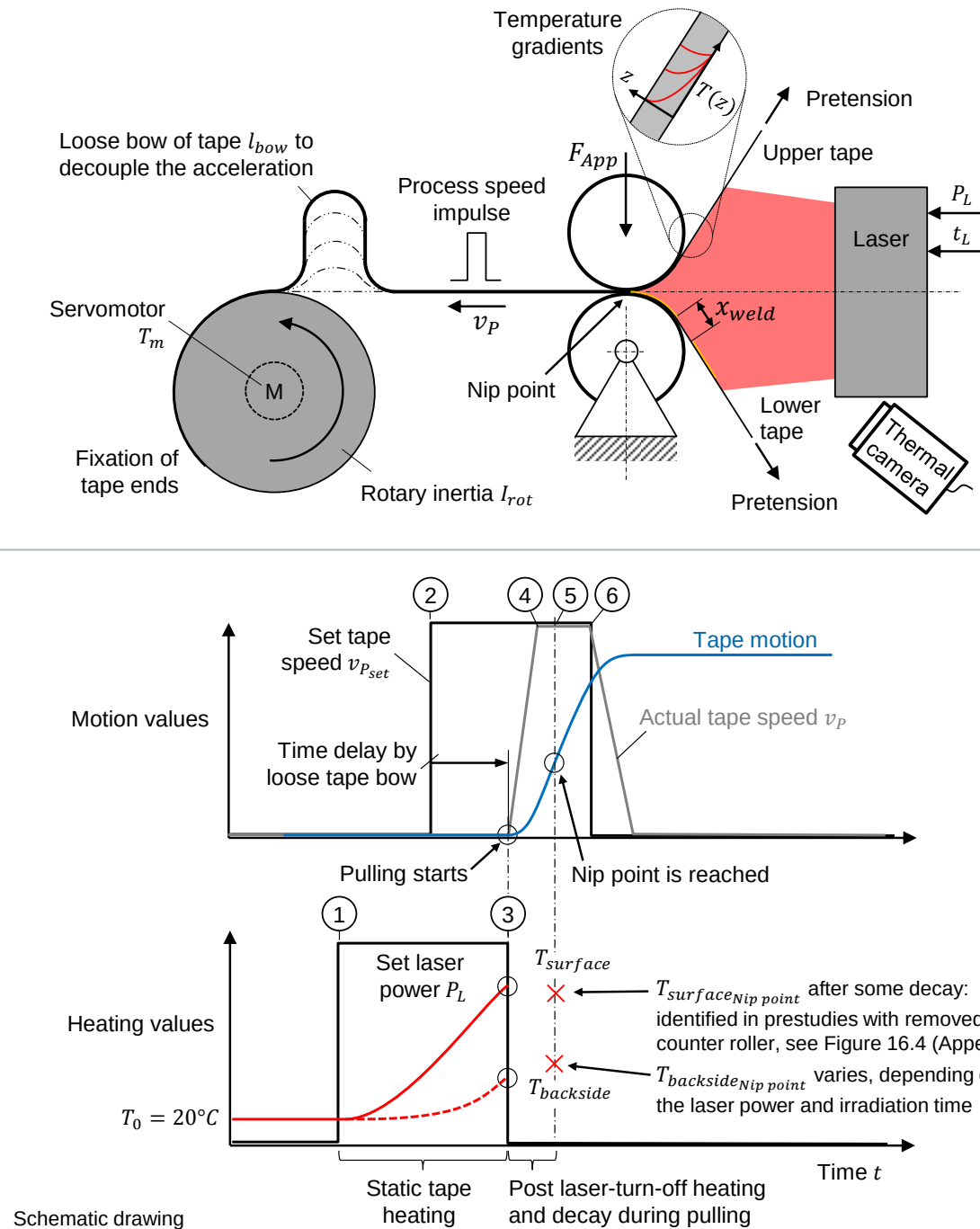


Figure 6.9: Top: Pull-through test for the bonding of two tapes with defined temperature conditions at defined process speed and consolidation pressure; Bottom: Principle process steps of the experiment with timed activations; extended pictures in the Appendix (p. 178)

Oben: Durchzugversuch zum Fügen zweier Tapes mit definierten Temperaturzuständen bei definierter Prozessgeschwindigkeit und Konsolidierungsdruck; Unten: Prinzipielle Prozessschritte des Versuchs mit zeitlich abgestimmten Aktivierungen; erweiterte Abb. im Anhang (S. 178)

Pretrials for Equal Surface Temperatures at the Nip Point. The main research objective of the experiment was to compare bonding processes of different temperature gradients yet *equal (nip point) surface temperatures*. For this to realize, pretrials were necessary, to find the exact moments at which the tapes had to be pulled. To get access to the nip point for (surface) temperature measurements, the lower counter roller was temporarily removed from the setup (Appendix, Figure 16.4, p. 183). In this setting, the parameters for the flashing of laser and servomotor were found (Figure 6.11, Figure 6.12, p. 117, 118). The actual temperature gradient during consolidation remained hidden, as the backside was inaccessible for measurements.

Laser Source. The available laser system imposed certain limitations on the maximum temperature gradients. A 1600-W VCSEL module was used. The laser rise and fall time was found to be negligible compared to motion processes. The laser and its holder for flexible positioning are shown in the Appendix, Figure 17.1 (p. 185).

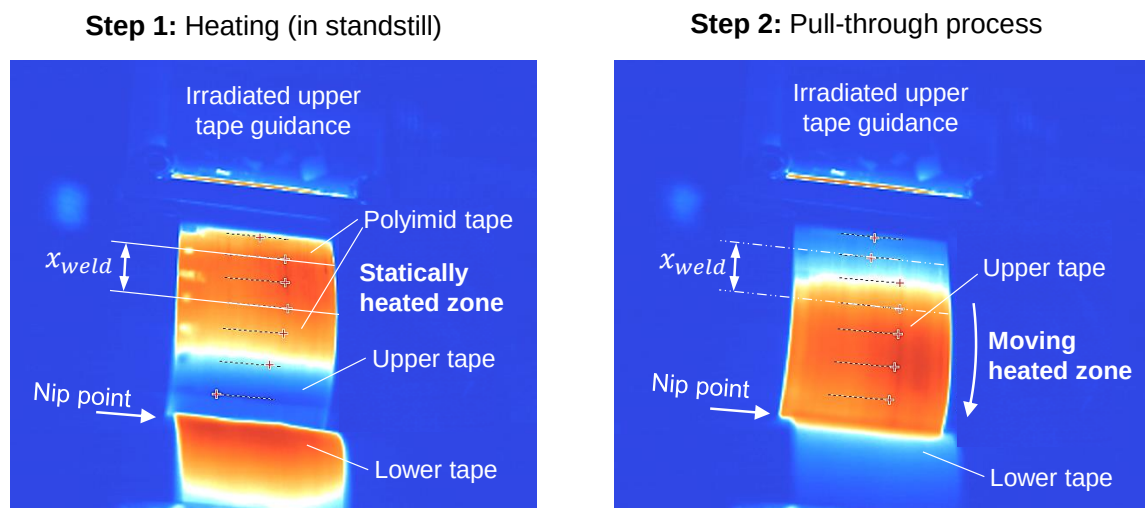


Figure 6.10: Validation of irradiation homogeneity of the weld zone (left); moving heated tape element (right). The view of the thermal camera is depicted in Figure 6.9.

Validierung der Bestrahlungshomogenität der Fügenschweißzone (links); bewegtes erwärmtes Tapeelement (rechts). Blickrichtung der Thermokamera ist in Abb. 6.9 dargestellt.

Heat Flux. The maximum surface heat flux $\dot{q}_0$ that can be induced with this type of laser is 1.2 W/mm². The maximum surface heat flux in the experiment was slightly lower: 0.75 W/mm². This was caused by the angular infeed of the tape (45°) and the absorption coefficient of the material: $\alpha \approx 0.9$ (Figure 15.2, p. 178). The heat flux was determined in optical simulations based on the works in [WEIL16b] and crosschecked with temperature measurements. The homogeneity of irradiation of the weld zone was validated in pretrials (Figure 6.10).

Tape Motion. As depicted in Figure 6.9, following the laser flash, the tape is immediately set in motion. The pyrometer stops measuring at this point, as it is pointing at the standstill position and unable to co-move with the tape. The pyrometer information was therefore not of interest after the pulling has started. Figure 6.10 (right-hand side) shows a thermal camera image of the moving (heated) tape element.

Following the initial pull (Position 3), the tape cools down slightly during its path to the nip point. Note that stronger temperature gradients cool out more rapidly than lower temperature gradients. Therefore, the probes of high gradients had to be slightly more overheated prior to the pulling (Table 6.2).

The distance from the standstill position to the nip point x_{pull} was 20 mm (Figure 6.7). Measurements showed that it takes 25-35 ms for the tape to reach the nip point – a sufficiently short period for the gradients in this study to remain high and affect the bonding process. The acceleration rate of the tape was difficult to detect, because the sampling rate of the signal acquisition device was > 8 ms (compare Figure 6.11).

It can be foreseen that investigations of even stronger temperature gradients will demand more powerful laser sources, higher tape acceleration rates and thus shorter sampling rates for more precise measurements (Figure 6.11 and Figure 6.12).

Consolidation System. The consolidation system consists of an aluminum consolidation roller and an opposite counter roller, both having a diameter d_R of 20 mm. The diameter was chosen to minimize the distance from the static heating position to the nip point. The rollers are guided by ball bearings; only the shell rotates, to avoid high inertias against the pulling. The rollers are mechanically connected to a pressure-controlled pneumatic cylinder (0 to 6 bar operating pressure; 0 to 130 N). This allowed investigations on the effect of consolidation pressure. The pressure length x_{App} was determined in a prestudy and found to be 1.5 mm, independent from the cylinder force. The average consolidation pressure $\bar{P}_{App}$ can be controlled from 0 to 3.5 N/mm² (0 to 35 bar), for the investigated 25 mm-wide tapes. The pressure length was determined by use of pressure-sensitive paper (*Prescale*® of Fujifilm, Figure 16.3, p. 183). Further tape guidances helped to prevent lateral movements of the tapes between the roller-roller consolidation system (Figure 15.2, p. 178).

Lap Shear Test and Bond Barriers. In previous studies it was found that thin adhesive Polyimide tapes can be used as bond barriers in combination the lap shear test, to obtain the weld strength of tape-placed probes [STOK16a, p. 21]. The distance between the Polyimide tapes defines the length of the weld zone x_{weld} (Figure 21.3, p. 203). The Polyimide tapes are expected to not influence the heat transfer near the weld zone significantly, because (a) it is 4 times thinner than the composite tape and (b) laser overlaps the weld zone left and right > 3 mm (see Figure 6.10). Furthermore, all experiments underwent *equal preparations* to ensure *comparability*.

The preparation method is well-suited for the pull-through test, because the consolidated probes are directly applicable for the lap shear test. Furthermore, a large number of probes can be made in a relatively short period of time. The lap shear test setup is shown in the Appendix, Figure 15.3 (p. 179). The probe preparation procedure is also shown in the Appendix, Figure 21.4, p. 203.

In the following, an initial investigation on the general effect of temperature gradients will be presented, using the novel experimental setup.

6.2.2 Experimental Design and Execution

Versuchsplanung und -durchführung

The presented pull-through test will be used for a first investigation on the effect of temperature gradients for a specific tape. This should be pointed out, as it is likely that different types of tape will lead to different results.

Material. The choice of tape for the experiments fell on HDPE/GF with a thickness of 0.25 mm. There were several benefits of using this material:

- The economic demand to process at high speeds is more urgent for HDPE/GF than for PEEK/CF (Figure 1.7), due to the large price difference.
- The tape is relatively bulky, so through-thickness conduction is not as limited as in thinner tapes; the effect of heat accumulation is minimized (Section 5.2).
- It is expected that higher material thicknesses induce more issues by the changing through-thickness elasticity $E(z)$ (Section 5.8).
- HDPE has a low melting temperature
- It is expected that a higher thermal diffusivity α induces more issues, due to higher cooling rates: $\alpha_{HDPE} > \alpha_{PEEK} \Rightarrow dT_c/dt_{HDPE} > dT_c/dt_{PEEK}$.

The melting temperature $T_{melting}$ of the tape was 127°C [CELA17]; the minimum thermal decomposition temperature $T_{degradation}$ of the HDPE is reported to be 233°C [BEYL02, p. 124]. The experiments were optimized for these parameters. The data of the material and a microsections are shown in the Appendix, Section 18.2.

Irradiation Scenarios. The experimental design was reduced to four set points: the *maximum* temperature ratio $K_{\Delta T}$ *inducible* with the laser source, and the lowest temperature ratio, investigated during the analytical study ($v_p = 55$ mm/s). Both temperature ratios were investigated for two different nip point surface temperatures: $T_{surface_{nip\ point}} = 190^\circ\text{C}$ and 165°C , $\pm 10^\circ\text{C}$. The data is summarized in Table 6.1.

Influence of Consolidation Pressure. To exclude cross correlations and sensitivities with other parameters, first the consolidation pressure was varied from 0.29 N/mm², 0.58 N/mm² to 1.85 N/mm² (2.9 bar, 5.8 bar and 18.5 bar). The influence was investigated for the low-temperature-gradient case at a nip point temperature of 190°C. Two probes of each parameter were made and tested for its lap shear strength (Figure 6.14, right-hand side).

Influence of Surface Roughness. Furthermore, the front side and backside of the tape – having a different surface roughness – were used to investigate the influence of the surface roughness on the weld strength. Measurements of the surface roughness are shown in the Appendix, Figure 18.3, p. 189. Again, two probes of each parameter setting were made and tested for the lap shear strength in the low-temperature-gradient condition with a nip point temperature of 190°C.

The general process flow of the pull-through test was already shown in Figure 6.8. The recordings of the processing data and measurements are shown in Figure 6.11 and Figure 6.12 (next pages). The key temperature measurements are documented in Table 6.2. Following the pull-through process, the probes were tested for their lap shear strength, as described in Figure 15.3, p. 179.

Table 6.1: Experimental design for the bonding of probes with different temperature gradients
Versuchsplan zum Fügen von Proben mit verschiedenen Temperaturgradienten

Nip point surface temperature*	Parameter	Low temperature gradient / high heat soak	High temperature gradient / low heat soak
165°C ±10°C	Laser power P_L	320 W	1600 W (max)
	Surface heat flux $\dot{q}_0$	0.15 W/mm ²	0.75 W/mm ²
	Irradiation time t_L	700 ms	100 ms
	Quasi process speed $v_{P_{quasi}}$	57 mm/s	400 mm/s
	No. of probes	3	3
190°C ±10°C	Laser power P_L	320 W	1600 W (max)
	Surface heat flux $\dot{q}_0$	0.15 W/mm ²	0.75 W/mm ²
	Irradiation time t_L	780 ms	130 ms
	Quasi process speed $v_{P_{quasi}}$	51 mm/s	307 mm/s
	No. of probes	3	3

*prestudies confirmed equal surface temperatures at the nip point after the pulling process, for the given parameters (Figure 16.4, p. 183)

Consolidation speed $v_P = 1000 \text{ mm/s}^{+0}_{-10\%}$ (in all cases)

Quasi heated length $x_{L_{quasi}} = 40 \text{ mm}$

Consolidation force $F_{App} = 65 \text{ N}$; pressure $P_{App} \approx 1.6 \text{ N/mm}^2$ (16 bar)

Table 6.2: Temperature data of the pull-through experiments
Temperaturdaten der Durchzugversuche

Nip point surface temperature*	Parameter	Low temperature gradient / high heat soak	High temperature gradient / low heat soak
165°C ±10°C	Max. surface temperature during heating $T_{surface_{max}}$	172°C	182°C
	Max. backside temperature during heating $T_{backside_{max}}$	110°C	< 74°C (pyrometer limit)
	Max. temperature ratio during heating $K_{\Delta T_{max}}$	0.53	< 0.25
190°C ±10°C	Max. surface temperature during heating $T_{surface_{max}}$	209°C	217°C
	Max. backside temperature during heating $T_{backside_{max}}$	129°C	< 74°C (pyrometer limit)
	Max. temperature ratio during heating $K_{\Delta T_{max}}$	0.5	< 0.2

*prestudies confirmed equal surface temperatures at the nip point after the pulling process, for the given parameters (Figure 16.4, p. 183)

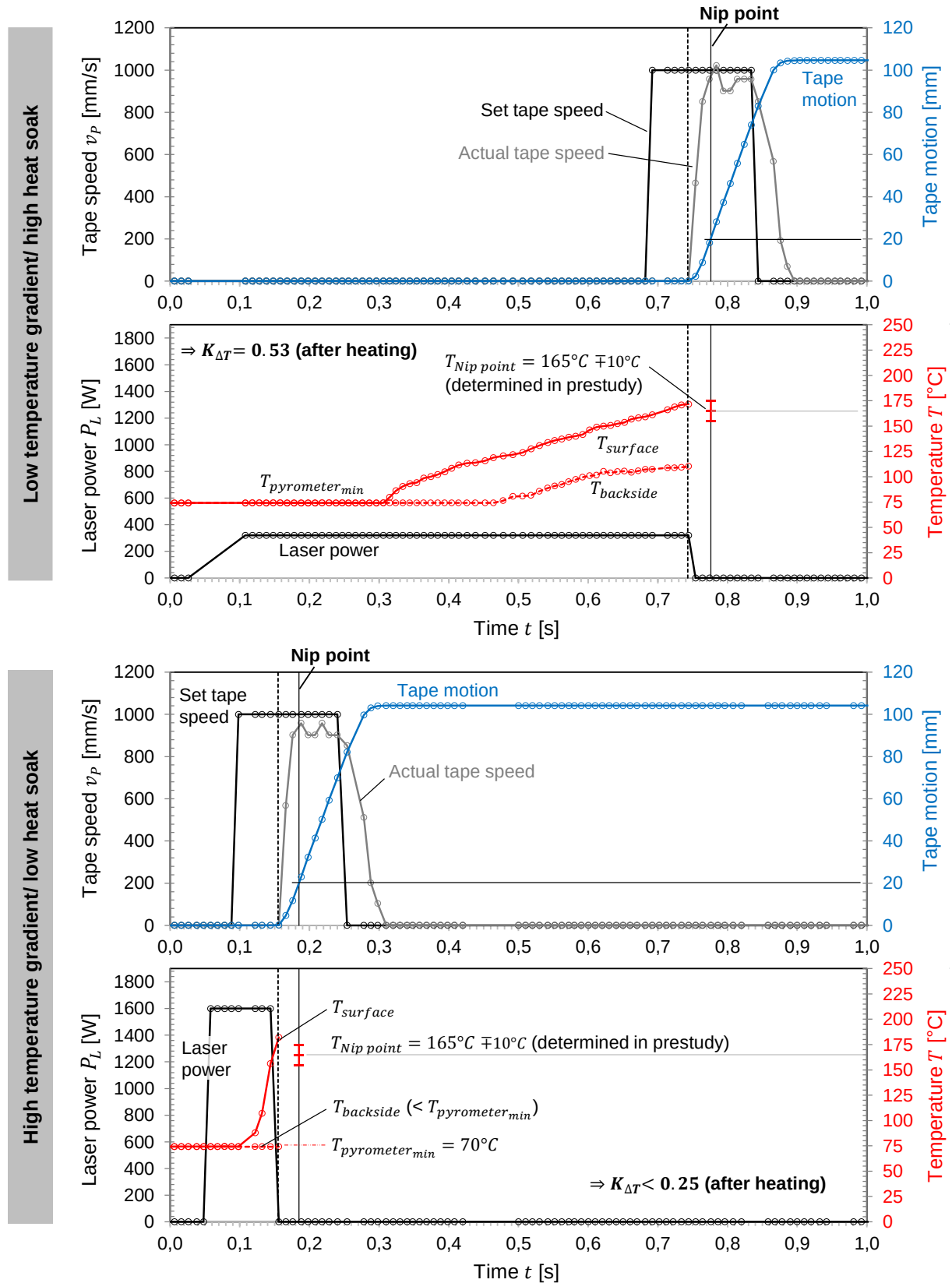


Figure 6.11: Recorded process data of the pull-through test with low thermal gradient (top) and high gradient (bottom), both with target temperature at the nip point of 190°C

Aufgenommene Prozessdaten des Durchzugversuchs mit eingestelltem flachen Temperaturgradienten (oben) und hohem Temperaturgradienten (unten), beide mit Zieltemperatur im Kontaktpunkt von 190°C

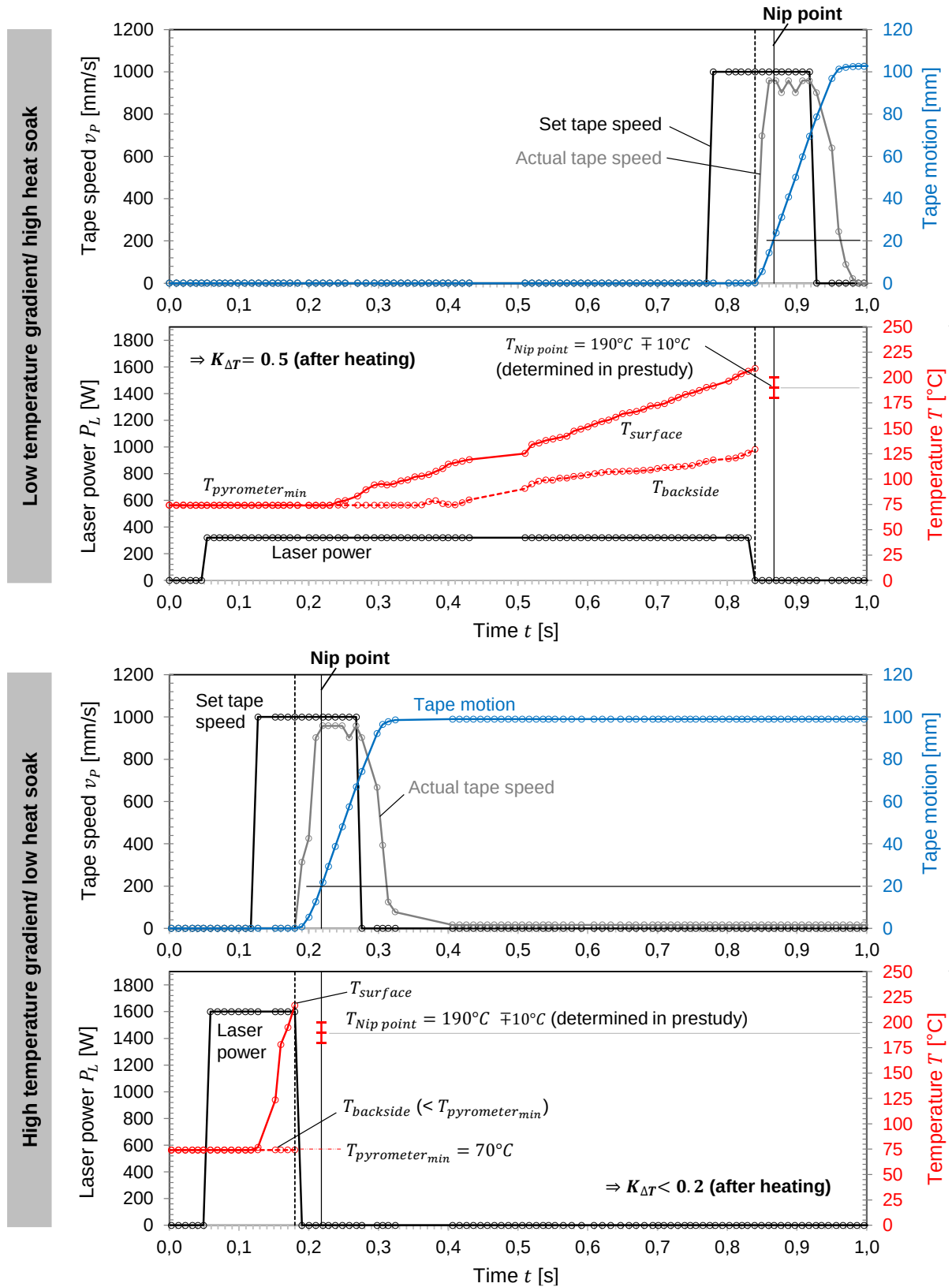


Figure 6.12: Recorded process data of the pull-through test with low thermal gradient (top) and high gradient (bottom), both with target temperature at the nip point of 165°C

Aufgenommene Prozessdaten des Durchzugversuchs mit eingestelltem niedrigem Temperaturgradienten (oben) und hohem Temperaturgradienten (unten), beide mit Zieltemperatur im Kontaktpunkt von 165°C

6.2.3 Results of the Lap Shear Test

Ergebnisse der Zugscherversuche

Probes were manufactured with the parameters given in Table 6.1. The probes were tested on basis of the lap shear testing method ASTM D5868 [ASTM14a]. The test setup is depicted in Figure 15.3, p. 179. The testing *speed* was taken from ASTM D3163 (2 mm/min), as the testing speed from ASTM D5868 (13 mm/min) led to issues in fracture behavior [ASTM14b]. Furthermore, the probes were fixed with abrasive paper to avoid slippage. In general, all probes elongated until an abrupt breakage occurred. The deviation among probes of equal process parameters was < 10%.

The tensile force measured at the point of failure F_f was used in combination with the measured weld length x_{weld} of $7\text{ mm}_{-0.7}^{+0.4}$ to obtain the lap shear strength τ_{weld} :

$$\tau_{weld} = \frac{F_f}{x_{weld} \cdot w_{probe}} \quad (6.6)$$

The width of the probe w_{probe} (14 mm) was established by edge trimming (Figure 21.3).

Reference Probe. To be able to compare the results with a maximum achievable weld strength $\tau_{weld_{max}}$, reference probes were manufactured under controlled conditions. The reference probes were consolidated within an oven under defined isothermal conditions, pressured by a metallic block of a defined weight and consolidation area. The setup is shown in the Appendix, Figure 15.4, p. 179. The maximum weld strength of the probes was found to be 14 N/mm². The tensile strength at break of a conventional HDPE is stated to be 12 N/mm² [SABI17].

Weld Strength Analysis. The results of the lap shear tests are depicted in Figure 6.13. It can be observed that the probes manufactured with low temperature gradients achieved in all cases – 165°C and 190°C – significantly higher weld strengths than the probes made with low temperature gradients – roughly 30%. It is expected that the surface temperature alone can therefore be excluded as the root cause for the difference in weld strength. The low temperature gradient probes differed from the maximum achievable weld strength by 6% for the high nip point temperature (190°C) and by 15% for the case of the low nip point temperature (165°C). In order to exclude other factors as causes for the weld strength difference, the influence of the surface roughness and consolidation pressure was investigated:

Influence of the Surface Roughness. The surface roughness of the tape was measured at the front- and backside. The two sides differed by a factor of 200% in their roughness (Figure 18.3, p. 189). After the surface measurements, the tapes were bonded in the pull-through test in a best-case surface roughness scenario (smooth-side-to-smooth-side) and worst-case scenario (rough-side-to-rough-side) (Figure 6.14). No significant deviation from the oven probes was found. In this measurement setup, some probes exceeded the strengths of prior experimental series (Figure 6.13, left-hand side, middle case and Figure 6.14).

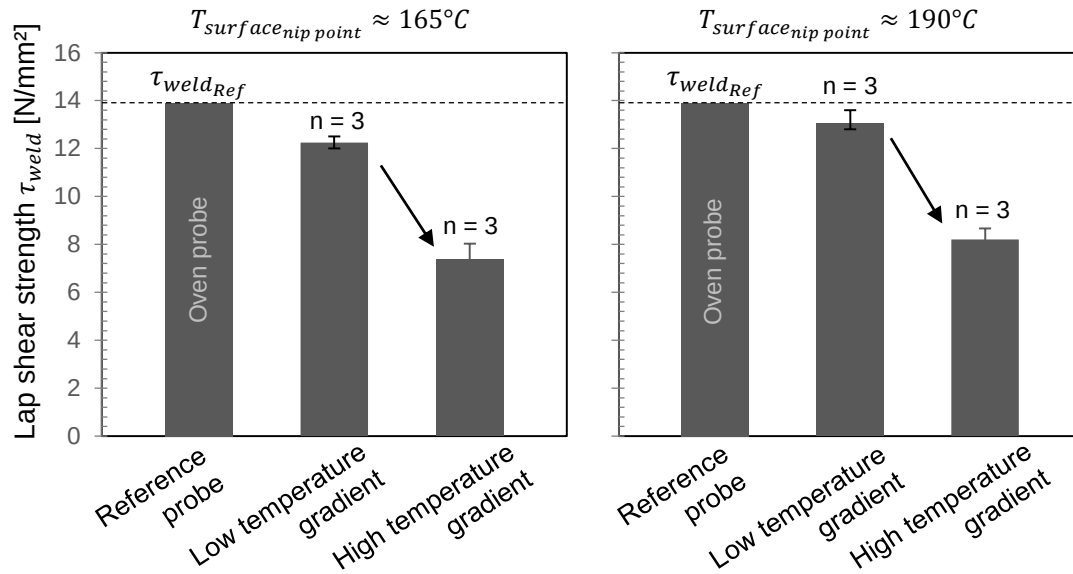


Figure 6.13: Lap shear strength of probes that were consolidated at equal nip point temperatures, but which exhibited different temperature gradients, with the use of 60 μm Polyimide tape as bond barrier

Zugscherfestigkeit von Proben welche bei gleicher Kontaktpunkttemperatur konsolidieren wurden, jedoch verschiedene Temperaturgradienten aufwiesen, bei Nutzung eines 60 μm Polyimid-Klebebandes als Fgetrennmittel

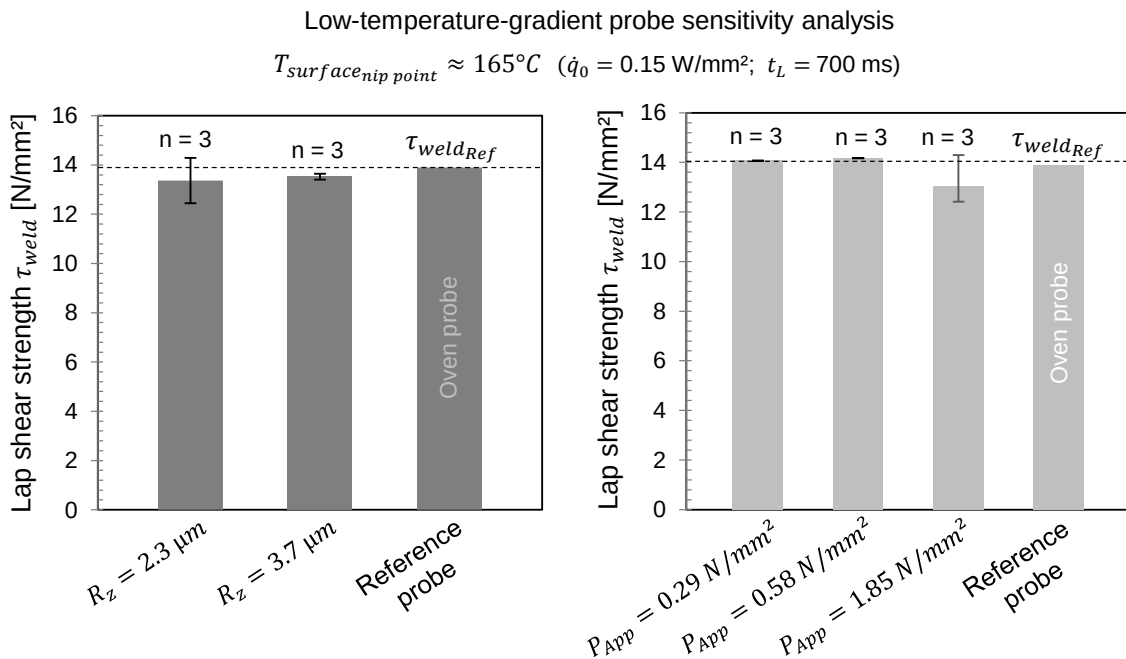


Figure 6.14: Lap shear strength of probes of different average surface roughness (left) and lap shear strength of probes consolidated under various pressures (right)

Zugscherfestigkeit von Proben verschiedener Oberflchenrauheit (links) und von Proben hergestellt bei verschiedenen Konsolidierungsdrcken (rechts)

Influence of Consolidation Pressure. As for the case of the surface roughness, the consolidation pressure showed no significant effect on the final weld strength (Figure 6.14, right-hand side). The maximum deviation from the reference probe was 11%.

6.2.4 Investigation of the Fractured Surfaces

Untersuchung der Bruchflächen

The fractured surfaces were investigated by microscopic imaging, to determine the cause of the observed weld strength reduction (Figure 6.15). At the top of the figure, the high-gradient probes are shown; the low-gradient probes are shown at the bottom. The probes on the left-hand side were manufactured with an equal nip point surface temperature of $165^{\circ}\text{C} \pm 10^{\circ}\text{C}$ and on the right-hand side with $190^{\circ}\text{C} \pm 10^{\circ}\text{C}$.

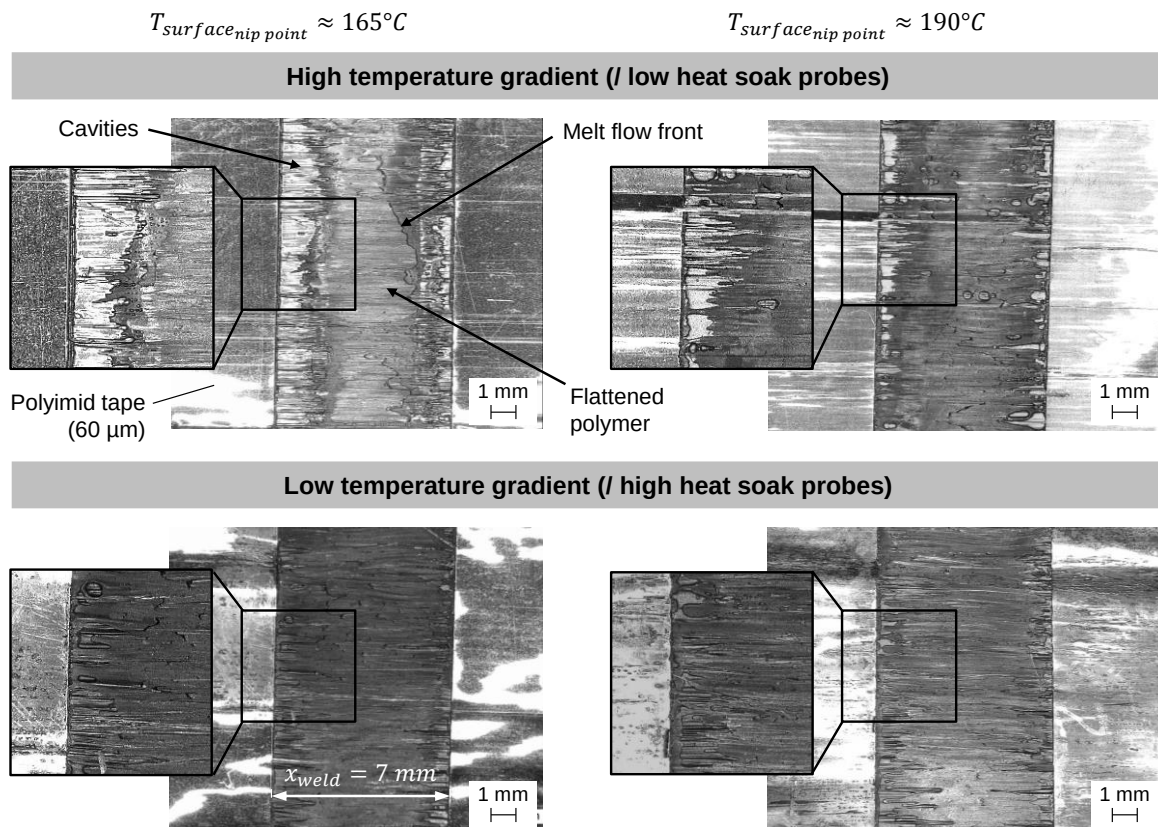


Figure 6.15: Microscopic images of the fractured probe surfaces. Top: probes manufactured with high temperature gradients (/ low heat soak). Bottom: probes manufactured with low temperature gradients (/ high heat soak)

Mikroskopaufnahmen der Proben-Bruchflächen. Oben: Proben hergestellt mit hohen Temperaturgradienten (/ geringer Wärmeaufnahme). Unten: Proben hergestellt mit geringen Temperaturgradienten (/ hoher Wärmeaufnahme)

It can be observed that the high-temperature-gradient probes exhibit large macroscopic cavities at the edges near the Polyimid tape. It is assumed that the step change of the Polyimid tape (unexpectedly) induced an obstacle for the melt flow. It can be observed that the step change was much more of an issue for the high-gradient probes. Those show much larger cavities of missing melt. *The 60 μm step induced a weaker bonding zone on the scale of > 2 mm, which amounts to a factor of > 30.* In the middle of the high-gradient probes a plateau of flattened polymer can be identified, which contributed to the strength of the 7 x 14 mm² weld zone.

On the surface of the fractured high-gradient probes, the melt flow front can be identified, especially on the surface of the top-left probe. It should be noticed that the Polyimid thickness of 60 μm is much larger than the surface asperities of the original tape, which are in the range of 2 to 4 μm – a factor of 15 to 30 (Figure 18.3).

Backside Probe Appearance

As already mentioned in Subsection 6.1.1, the condition of the tape backside can be relevant for a number of aspects, e.g. appearance of the final laminate surface or for the basis for subsequent bonding processes in follow-up layers.

The high-gradient and low-gradient probes differed in this respect significantly. Figure 6.16 shows two typical backside appearances of the probes. Whereas the high-gradient probes are not affected by the consolidation process at all, the low-gradient probes show large areas of temporarily molten polymer with a squeezed-out fiber structure at the center. This was expected because the recorded backside temperature exceeds the melting temperature (please see the red curves at top of Figure 6.11).

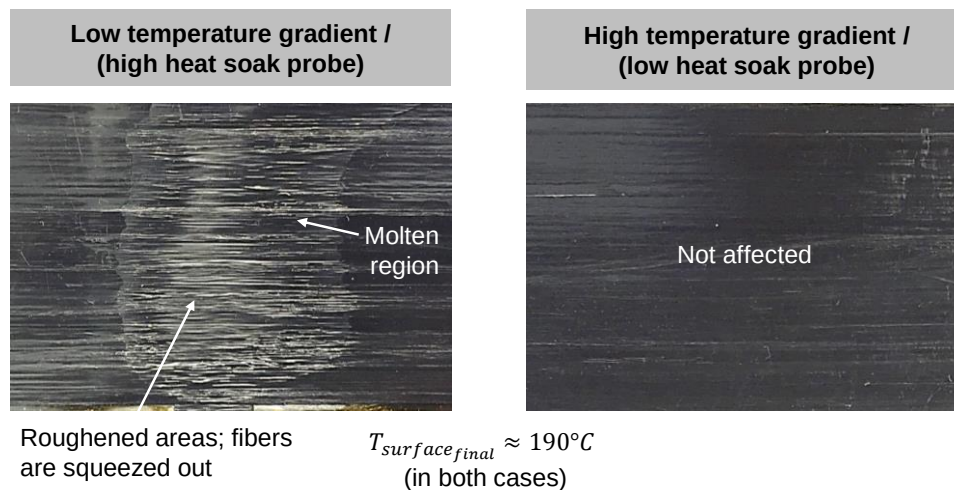


Figure 6.16: Backsides of the probes from processes with different temperature gradients. Both probes were heated to equal surface temperatures at the front side. Process parameters are documented in Table 6.1 and Table 6.2.

Proben-Rückseiten aus Prozessen mit unterschiedlichen Temperaturgradienten. Beide Proben wurden auf die gleiche Vorderseitentemperatur erwärmt. Prozessparameter sind in Tabelle 6.1 und 6.2 dokumentiert.

The images show the effect of the temperature gradient on the backside of a tape after its laydown. In this respect, high-temperature gradients are generally beneficial for both a flat/smooth surface appearance as well as the development of intimate surface contact in subsequent layers. The squeezed-out fiber structure at the molten backside (left side) roughens the surface. Considering Equation 6.1, this would be tantamount to a change of the parameter R^* for the substrate side. The original roughness increased from the smaller asperities (0.6-2.3 μm) to at least the size of the (glass) fibers of > 10-20 μm (compare left side to right side in Figure 6.16 and Figure 18.2, Appendix). Intimate surface contact development will therefore be impeded.

6.2.5 Interpretation and Consequence of the Results

Interpretation und Konsequenz der Ergebnisse

Tape pieces were bonded at near-equal surface temperatures, yet different temperature gradients and tested for their lap shear strength. A Polyimid tape of 60 μm thickness was used to isolate the bond width. The high-gradient probes showed large areas (1-2 mm) of poor consolidation at the edges of the Polyimid tape. The tapes used in this initial study offered a relatively resin-rich surface layer of $\approx 25 \mu\text{m}$ (Figure 18.2, p. 188), which was expected to support a the filling of larger cavities. The experiments however demonstrated that the consolidation of such (high-quality) tapes becomes more problematic with higher temperature gradients. Whereas the probes consolidated with low temperature gradients showed a complete filling of the weld zone, the high-temperature-gradient probes lacked such a compensating effect.

Interpretation. It is assumed that the low-temperature gradients process provided a *deeper melt pool* to be squeezed into the cavities and a *lower rigidity* against a bending at the edge of the Polyimid tape (Figure 5.16). These phenomena were already assumed by STEYER and can be confirmed at this point [STEY13, p. 62-63].

Negative Consequences. Surface waviness of $> 50 \mu\text{m}$ are common features of laminates, especially in laminates with multiple layers. Tapes already have thicknesses of $> 100 \mu\text{m}$, so gaps/overlaps and tape crossovers alone, do lead to surface cavities/ripples larger than the applied Polyimid tape [COGS92, p. 131]. It is therefore expected that process speeds $> 500 \text{ mm/s}$ require increasingly flat substrate surfaces, to achieve complete bonding over the whole part surface.

Positive Consequences. Interestingly, higher speeds also show a positive attribute in this respect: the occurring higher temperature gradients keep the tape backside in its initial flat/smooth state. The fibers remain fixed within the solid polymer; the original surface condition remains intact (Figure 18.2):

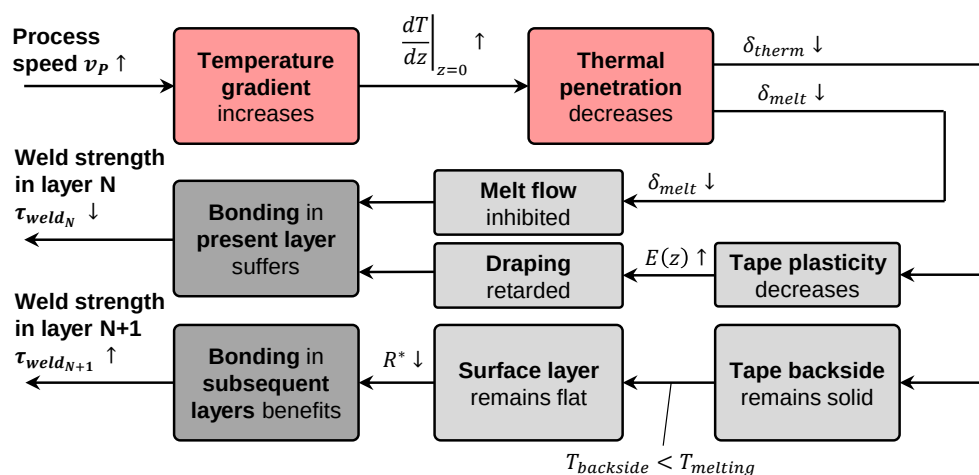


Figure 6.17: Positive and negative aspects of high temperature gradients at high speeds on the bonding process in initial and subsequent layers

Positive und negative Aspekte thermischer Gradienten bei hohen Prozessgeschwindigkeiten auf den Fügeprozess in ersten und nachfolgenden Lagen

Conclusion for Parameter Settings. It therefore appears that a conflict of interest exists for high-speed processing of tapes (with conventional systems): Stronger temperature gradients create smoother laminate surfaces but limit the melt flow for the filling of cavities and stiffens the tape. At the point at which the backside remains solid, further increase of the gradient seems to be unfavorable for subsequent consolidation processes. It is therefore concluded that:

The temperature gradient should be steep enough, to keep the tape backside in a solid state (not molten) and thereby flat and smooth; but not steeper, to support polymer melt flow at the front side and to support the draping process.

In state-of-the-art tape placement systems (with fixed irradiation profiles) it is not possible to control $T(z)$. Instead, the phenomenon is merely the consequence of process speed and laser power.

Conclusions for Tape Attributes. Thick surface polymer layers ($> 20 \mu\text{m}$) are expected to be generally beneficial for the observed phenomena. However, in tapes with low-cost fibers, like HDPE/GF, the polymer takes up a large part of the material cost, so unnecessary thick surface layers increase the final part cost. The use of thicker tapes seems to be an appropriate solution to the problem; however, spoolability, tape guiding and additional manufacturing cost for impregnation have to be kept in mind. Reducing the thermal diffusivity of the polymer by additives could improve the situation.

Conclusion on the Derived Limitations. A specific limit for autohesion and intimate surface contact development could not be demonstrated yet; the available laser power to induce the required temperature gradients was simply too low. Both mechanisms can be excluded as causations for the observed lower weld strengths, because:

- The high temperature gradient probes lacked a polymer filling at *both* sides of the weld zone, so prior cool out of the melt can be excluded.
- After subtraction of the unbonded polymer area, which makes up $\approx 30\%$ of the overall weld zone, the bond interface strength equals the level of the low-temperature-gradient probes ($\approx 12 \text{ N/mm}^2$).

Further research is required with more powerful laser sources and higher tape acceleration rates, to impede autohesion or intimate surface contact development.

Nonetheless, another critical effect on the weld strength was discovered, which was not anticipated at first: Cavities (or surface steps) of $> 50 \mu\text{m}$, which are a common feature of tape-laid surfaces, are more prone to be bonded with polymer when the material is heated with high temperature gradients. In general, the spectrum of research on the effects of temperature gradients is largely untapped today. The presented pull-through test may be a practical tool for efficient future investigations.

It must be noted that the melt squeeze into the cavity can also be improved by the use of elastic rollers with higher pressuring lengths. Rigid rollers, used in the experiment, achieve a pressuring length of $< 2 \text{ mm}$ [SONM97b, p. 405], whereas elastic rollers are reported to achieve pressure lengths of up to 28 mm [STOK14, p. 107].

7 Analysis of Irradiation Strategies for a Controlled Through-Thickness Temperature Distribution

Analyse von Bestrahlungsstrategien zur Steuerung der Temperaturverteilung in Materialdickenrichtung

The previous chapter described several effects of the through-thickness temperature distribution on the consolidation and laydown process. The experimental investigation demonstrated negative aspects of high gradients – thinner polymer melt pools and higher rigidity (Subsection 6.2.3). A lot more research is required, to quantify all effects of temperature gradients and their cross correlations with material properties.

Notwithstanding the above, being able to *control* the through-thickness temperature distribution will likely be of technological interest in the future, not only for thermoplastic tape placement, but maybe for other *additive* processes, where the *process speed* is a crucial parameter (and the materials thermal diffusivity relatively low). For tape placement machines, two major reasons for improvements were identified:

First Reason. Due to the economic demand for higher output (kg/hr), Figure 1.7 (p. 11), the process speed is likely to become a major optimization target in the future; advances in manipulator technologies towards more dynamic systems, e.g. [ASHA17], will encourage this trend. The required laser power is already available today with powers of > 30 kW [LASE13]. Increasing the process speed from 55 mm/s to 2000 mm/s induces significant changes in the melt pool conditions, which cannot be compensated today.

Second Reason. Several more aspects for and against high temperature gradients have been identified during the course of this thesis (Table 14.1, p. 175). It is not possible at the moment to adapt the irradiation for one of these aspects. It is also not possible to adapt the irradiation to the prevailing material properties, like tape thickness / thermal diffusivity or to the machine attributes, like the pressuring length of the consolidation roller.

In general, it is postulated that:

For any combination of consolidation system and tape attributes there exists an optimal through-thickness temperature distribution $T(z)$ for maximized bonding quality at minimized cost. $T(z)$ changes with increasing process speed. Therefore, the laser irradiation distribution $I(z)$ in tape placement systems should ideally be adaptable to the speed at which a respective tape is processed.

This section will analyze different laser irradiation *strategies* on their pros and cons for the heating process and for system integration in tape placement heads. In general, three irradiation strategies will be distinguished: (1) Maximization of the surface temperature [STOK16b, p. 194], (2) Adaptation of the irradiation time via the irradiation length [AGAR92, p. 121, 124], and (3) Decaying intensity distributions (Figure 7.1, p. 126) [STOK16b, p. 192]. These irradiation strategies have not yet been analyzed in detail and not *compared quantitatively*.

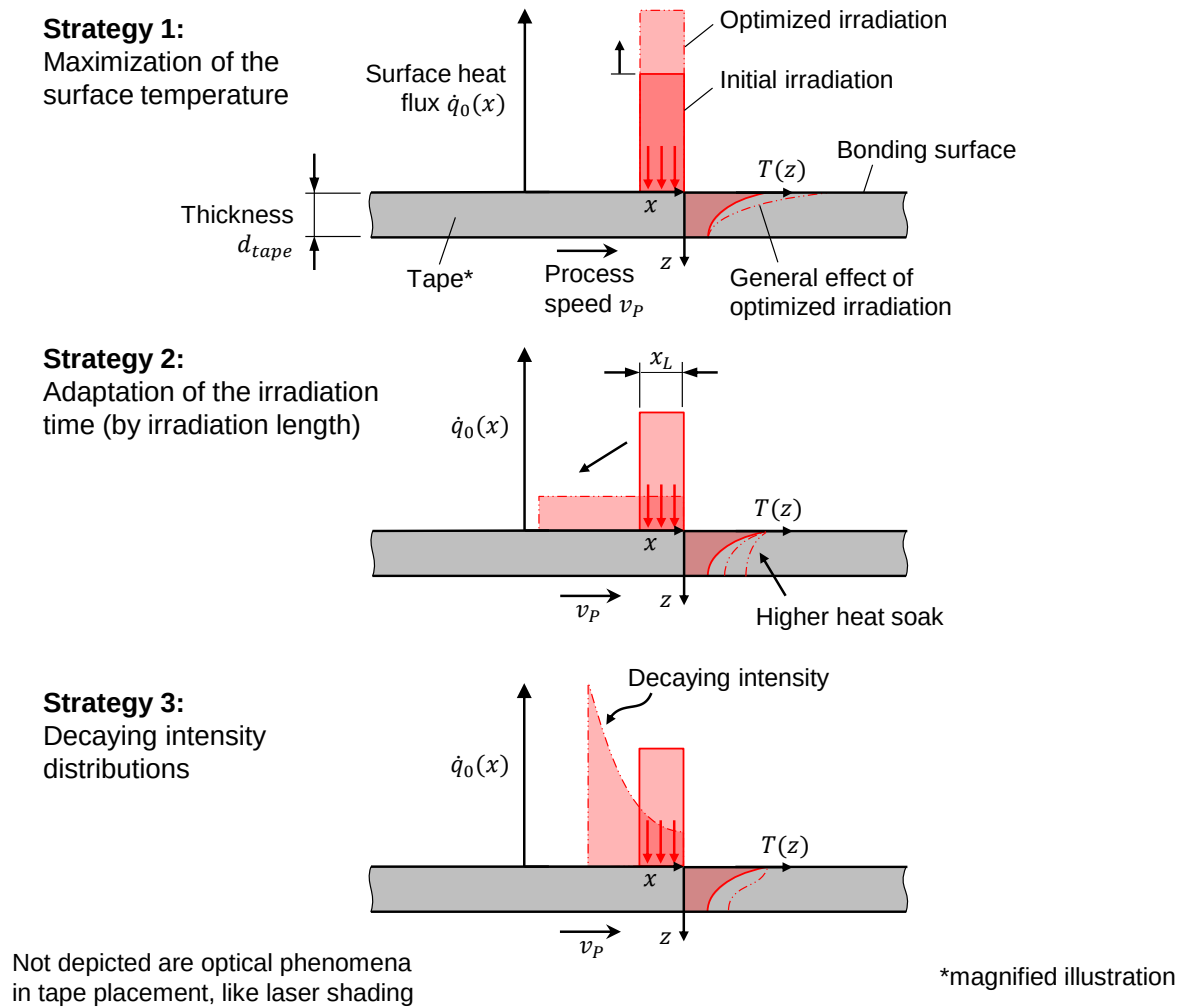


Figure 7.1: Overview of irradiation strategies for the influence of the through-thickness temperature distribution

Übersicht von Bestrahlungsstrategien zur Beeinflussung der Temperaturverteilung in Materialdickenrichtung

It has to be noted that none of the irradiation strategies is mutually exclusive. However, to demonstrate their specific effect, they will be analyzed separately. The practical implementation of the strategies depends on the market-available laser technologies.

Scenario Analysis. The strategies will be analyzed separately on basis of a hypothetical high-speed process scenario: the initial condition in the scenario is a process speed of 2000 mm/s, using PEEK/CF tape of 0.25 mm thickness and a substrate of semi-infinite thickness. The time-dependent temperature development $T(z, t)$ during such a process speed was already presented in Figure 5.4 and Figure 5.5, p. 77-78. In this initial scenario, the melt pool depth (per body) is 15 μm (≈ 2 carbon fiber diameters) and remains molten for less than 3 ms, until solidified again. (The mean diameter of a human hair is $\approx 60 \mu\text{m}$). This exceptional thermal condition is expected to cause issues for both autohesion as well as intimate surface contact development (please compare Figure 6.2 and Figure 6.3, p. 101, 103).

In the following the irradiation strategies will be used to improve the situation.

7.1 Strategy 1: Maximization of the Surface Temperature

Strategie 1: Maximierung der Oberflächentemperatur

The first strategy to influence the through-thickness temperature distribution is to overheat the surface. This is a feasible method, as long as the surface polymer does not exceed the degradation temperature. Maximized surface heating has the additional positive effect of minimized surface viscosity $\mu_0(T)$, which supports intimate surface contact development (Figure 6.2).

Limit of the strategy. The maximum temperature $T_{heating_{max}}$ can be derived by subtraction of the melting temperature $T_{melting}$ and the maximum control tolerance $\Delta T_{control_{max}}$ from the degradation temperature $T_{degradation}$:

$$T_{heating_{max}} = T_{degradation} - T_{melting} - \Delta T_{control_{max}} \quad (7.1)$$

The equation reveals already the limitation of the strategy: After the laser power has been increased to the point at which the surface temperature equals the degradation temperature – assuming ideal controls –, the limit is reached. Further increase of $T_{surface}$ would lead to a thermal decomposition of the polymer (Figure 20.2).

Case Analysis. To improve the presented scenario (from p. 125) the laser power will be increased by a factor of 1.34, from 2.9 kW to 3.9 kW, leading to a surface temperature of 550°C, 50°C below definite degradation. The resulting change in the through-thickness temperature distribution is depicted in the subsequent figure:

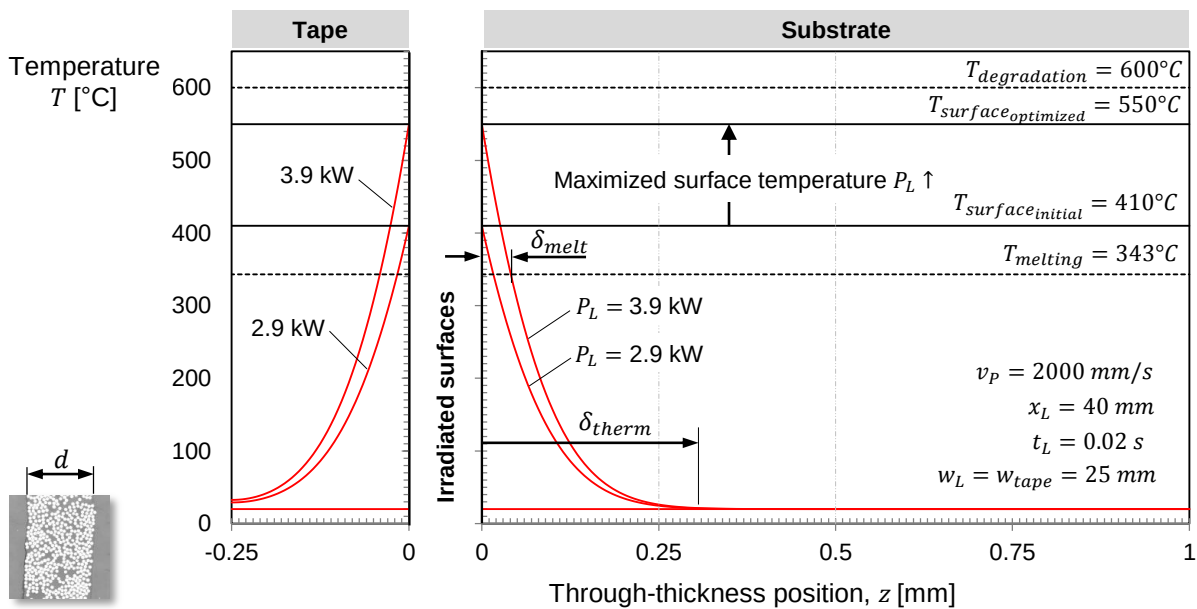


Figure 7.2: Effect of maximized surface temperature from 410°C to 550°C on the melt pool depth and temperature distribution after heating

Auswirkung maximierter Oberflächentemperatur von 410°C auf 550°C auf die Schmelzbadtiefe und die Temperaturverteilung after heating

It can be observed that the temperature gradient near the surface increases slightly. This is because $dT/dz|_{z=0} = -\dot{q}_0/k_z$ and $\dot{q}_0 \sim P_L$ (Figure 4.8, p. 60). The thermal penetration δ_{therm} remains equal. Equation 4.10 predicts this behavior. Still, the melt

pool depth δ_{melt} increases by a factor of 2.2, from 15 μm to 33 μm . The thermal energy demand increases by a factor of 1.34 (proportionally to the laser power, Equation 2.3). The initial cooling rate increases slightly, due to the steeper gradient near the surface. However, the conductive cooling to reach $T_{melting}$ remains similar, as the bond interface temperature T_{bf} starts to drop at a higher level (550°C instead of 410°C).

Laser System Technology. The practical implementation of this strategy requires no additional efforts: As most of today's tape placement machines are equipped with closed-loop (surface) temperature controls, the strategy requires merely the setting of a higher surface temperature value (Section 2.3). However, the accuracy of the control has to be monitored more precisely. Minor overshoots will inevitably lead to the degradation of the surface polymer. The closer the setpoint value is to the degradation level, the more sensitive this issue becomes. The accuracy requirement for the closed-loop control is therefore expected to increase with this strategy. Unwanted optical and thermal fluctuations during practical processing however, work against this requirement, see [COUR17, p. 15-22] and Subsection 2.2.2 and 2.2.3; the same applies for inhomogeneities of the surface temperature (Figure 5.9, p. 85). It can also be foreseen that small deviations of the laser power or tape motion lead to larger deviations of the surface temperature, which is unfavorable for the control accuracy.

7.2 Strategy 2: Adaptation of Irradiation Time (~Length)

Strategie 2: Anpassung der Bestrahlungszeit(~strecke)

The second strategy pursues to influence the thermal penetration δ_{therm} by increasing the irradiation time t_L via its proportionality to the irradiated length x_L . The fundamental correlation is represented by Equation 4.10, p. 59. Longer irradiation lengths provide the material more time to transfer ("soak up") the heat. The determining physical barrier to overcome is the fixed thermal diffusivity α of the material. This strategy has been mentioned *qualitatively* by previous authors (Subsection 2.2.4); however, a detailed description of the correlation between irradiation length, process speed, laser power and temperature gradient is missing so far. Figure 8.2 will present such a description.

Case Analysis. To improve the presented scenario (from p. 125) several adaptations are possible. The chosen optimization target is to change the through-thickness temperature distribution in such a way that the backside remains $< 300^\circ\text{C}$ ($< T_{melting}$), without changing the surface temperature. In this setting, the backside remains solid, even after the temperature gradient has equalized from internal cooling by conduction (Subsection 6.2.5). The result is shown on the next page in Figure 7.3; surface overheating would be possible as well, but is left out for demonstration purposes.

To realize such a scenario, the irradiation length x_L has to be increased by a factor of 10, from 40 mm to 400 mm. The laser power P_L has to be adjusted accordingly, from 2.9 kW to 9 kW for the case of the semi-infinite substrate, and from 2.9 kW to 7.6 kW for the case of the finite tape. Notice the different requirement for the thin tape and the thick substrate, caused by the heat accumulation effect in the tape.

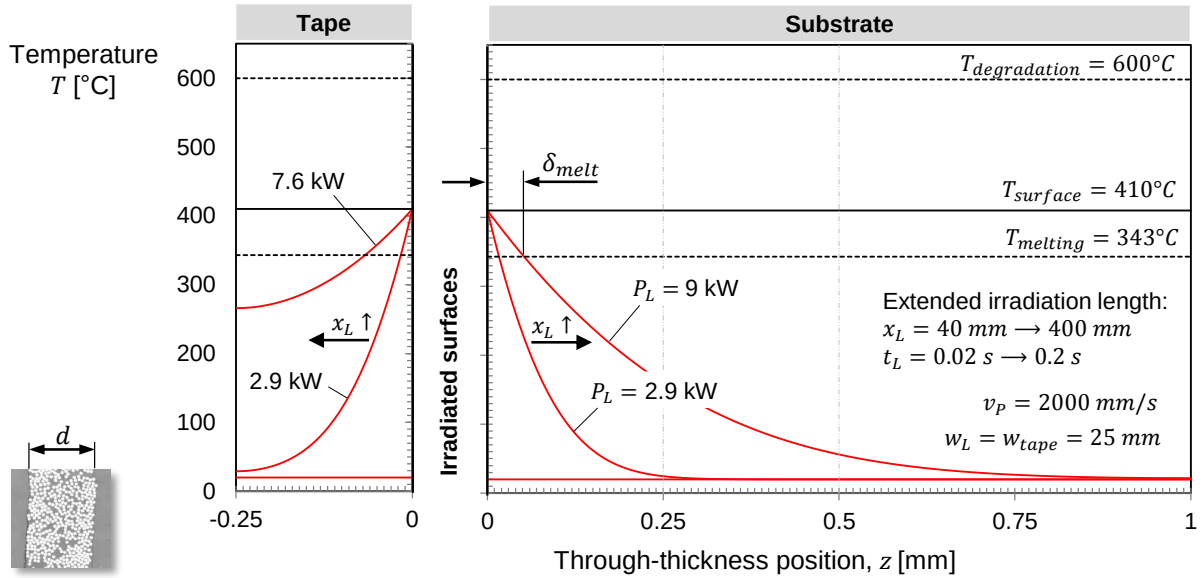


Figure 7.3: Effect of increased heated lengths (by a factor of 10) on the melt pool depth and temperature distribution after heating

Auswirkung einer erhöhten Bestrahlungslänge (vom Faktor 10) auf die Schmelzbaddtiefe und die Temperaturverteilung after heating

Observations. The melt pool depth δ_{melt} increases by a factor of 3.6, from 16 μm to 58 μm . The strongest impact concerns the melt dwell time t_{melt} : it increases by a factor of 10, quite proportionally to the extended irradiation. The thermal energy demand for 1 kg placed mass of tape (Equation 5.2, p. 75) increases by a factor of 2.86 (from 148 to 387 kJ for the case of the tape and from 148 to 459 kJ for the substrate). Notice again the lower energy demand for the tape, supported by the heat accumulation.

Finally, observe the higher temperature in previous layers. This higher thermal penetration can support repetitive consolidation and healing in subjacent bond interfaces, especially if thinner tapes are processed, e.g. $< 0.15 \text{ mm}$, and the surface temperature is additionally maximized.

Practical Difficulties and Application Case. With higher irradiation lengths, the thermal control during start/stop becomes more of a challenge, as the material generally has to pass through the whole heating zone. However, in winding processes, especially continuous winding processes, this issue can be solved quite easily: The irradiation length can be increased gradually during the manufacturing cycle, according to the winding speed. Laser technologies for adaptive heating length are available on the market. Section 2.1 presented already some of them. In Chapter 9, motorized zoom homogenizers and the VCSEL technology will be considered in more detail on their applicability (Figure 9.1 and Figure 9.2, p. 139, 141).

It was found that longer heating lengths (at higher speeds) do not influence the heat losses, because $\dot{Q}_{conv}$ and $\dot{Q}_{conv}$ are negligible. Furthermore, the convective heat transfer coefficient $\bar{h}_{conv}$ and the exposure time to air (t_L) remain equal (Section 19.1).

7.3 Strategy 3: Decaying Laser Intensity Distribution

Strategie 3: Abnehmende Laserintensitätsverteilung

The third strategy to impact $T(z)$ is to customize the surface heat flux profile $\dot{q}_0(x)$ via the laser intensity *distribution* $I_L(x)$. This strategy bases on the effect that high surface heat fluxes create a rapid near-surface temperature rise, which in turn leads to a higher heat transfer over a shorter period of irradiation (Equation 4.6). The strategy has first been proposed for tape placement by STOKES-GRIFFIN & COMPSTON [STOK16b, p. 194]. Their proposed intensity profiles were revised in Figure 2.15 (p. 33). The first experimental study of the strategy was presented in [WEIL18] by use of VCSEL.

In general, the strategy is very promising, as it is possible to induce a wide variety of temperature distributions, if the required laser intensity distributions $I_L(x)$ can be computed and implemented on a system level. It is also a promising strategy because decaying irradiations lead to a higher thermal penetration δ_{therm} over a shorter heated length x_L . The described issues on the previous page can be reduced.

Restrictions. The shaping of $T(z)$ is only limited by the degradation temperature of the polymer, because momentary surface temperature overshoots above $T_{degradation}$ must be prevented. The strong laser intensities can lead to high heating rates and thereby to surface temperature overshoots, especially in case of false motion profiles or material standstills (compare Figure 2.15, p. 33). However, in general, this strategy is quite beneficial for start/stop procedures, because of the minimized heating length.

Challenges in Computation and Practical Implementation. Note that the heat transfer response of decaying heat flux profiles $\dot{q}_0(x)$ is fundamentally different from the responses described in this thesis. The equations presented are not applicable, which is another challenge of the strategy: In order to *predict* the required $\dot{q}_0(x)$, an *inverse* thermal FE simulation is required in which multiple iterations of FE simulations automatically find the closest solution, like the one presented in [VOEL16]. Such tools can take up a lot of computation time and no ready-to-use software solution is available on the market. A novel *inverse analytical* method was presented in [WEIL18].

Furthermore, the computed heat flux profiles $\dot{q}_0(x)$ have to be transferred to a desired laser intensity profile $I_L(x)$, which requires further *optical simulation tools* to generate a respective optical element, like a lens. Expertise in the manufacturing of free-form lenses is also necessary: The CAD data of the lenses must be converted into CNC code. As of today, all these steps require special-purpose engineering [KLOC17]. Finally, minor false positioning of the free-form lens(es) can lead to significant changes on the target surface. The environment in tape placement heads, with high accelerations and vibrations, seem to work against the implementation of such advances.

Thus far, only *fixed* free-form lenses have been discussed. In order to realize *adaptable* decaying irradiation profiles (to respond to changing process speeds), further advances in laser system technology are necessary. Semiconductor lasers, like VCSEL, are a promising candidate for such advances [MOEN15].

7.4 Concluding Evaluation

Abschließende Bewertung

Table 7.1 shows a comprehensive evaluation of the presented irradiation strategies. The upper part of the table concerns the pros/cons of the process; the lower part discusses laser system technologies and addresses the practical and economic concerns, like design space or investment cost.

It has to be emphasized again that the irradiation strategies and are not mutually exclusive. A free-shaped irradiation profile can – in principle – change its irradiation length and the maximization of the surface temperature is possible in all cases. The same holds true for the systems, which can be combined synergistically.

Table 7.1: Comparative evaluation of irradiation strategies and laser system technologies
Vergleichende Bewertung der Bestrahlungsstrategien und Lasersystemtechniken

Irradiation strategy	Maximization of surface temperature	Adaptation of irradiation time (~length)	Decaying intensity distributions
Attributes			
Range of temperature distributions $T(z)$	Very limited ($\rightarrow T_{degradation}$)	Extended, but intertwined with material properties	Highest; limited only momentarily ($T_{degradation}$)
Effect on the melt pool depth δ_{melt}	Limited	Not limited	Positive, but limited
Influence on the melt dwell time t_{melt}	Low	High	Medium
Influence on bond interface cooling rate	Very limited	High	Medium
Risk of degradation	High	Lowest	Medium
Req. laser intensity	High	Low	Very high
Energy efficiency	Good, if specifications can be addressed	Medium: Leads to more heat input	Good; can be designed for the specifications
Simulation effort for planning and controls	Non	Medium (Figure 8.2)	High: Inverse FE simulation required
Start-stop difficulties	Low	High; irradiation has to change in time and space	Medium; risk of overheating

Proposed laser system technology	Laser power control	Zoom homogenizers	VCSEL	Tailored free-form lenses
Attributes				
Estimated effort / capital investment	No additional cost	Medium: solutions available, but must be integrated		High: special-purpose optic design & manufacture
In-situ adaptability	Medium	Good	Very good	Low
Design space /weight	No additional efforts	Very high		Medium
Controls effort	Low	High		Low
Final assessment	Limited strategy; high risk of polymer degradation	Feasible strategy		High potential, but high effort to realize
Application case	Optimizing status-quo systems	(Continuous) winding systems		Tape laying systems

The feasibility assessment is based on the current state-of-the-art in laser system technologies. Future progress will certainly make new scenarios possible. Increasing the intensity and collimation of VCSEL could be such a relevant development.

8 Speed-Adaptive Control of the Temperature Gradient by Adaption of the Heating Length

Geschwindigkeitsangepasste Steuerung des Temperaturgradienten durch Adaption der Bestrahlungslänge

In conventional closed-loop temperature controls, the surface temperature $T_{surface}$ is utilized as process variable and the laser power P_L as manipulated variable [SCHM94, p. 85-108] [KOEL08, p. 79-89] [BREC14a, p. 51]. The current focus of research and development lies therefore on obtaining and controlling the surface temperature accurately and in short response times. Thermal imaging cameras and advanced data analysis are used to achieve this task [BREC16] (Figure 2.16, p. 36).

Drawbacks and Forecasted Future Issues. A drawback of the surface temperature control appears to be the negligence of the through-thickness temperature distribution. Current controls are basically “blind” to the thermal state *inside* the material. In today’s placement systems, the thermal condition is merely an *unintentional consequence* of the parameter setting process speed, laser power and surface temperature.

With higher available laser power on the market, more dynamic manipulators, and increasing demand for productivity, the process speed is likely to become a major optimization target in the tape-laying industry. As shown in Figure 5.2, higher process speeds shift the temperature distribution towards steeper gradients with the consequence of a thin thermal skin layer, thinner melt pools and higher rigidity of the tape during its laydown.

It is expected that on average, the melt pool depths, dwell times and the tape plasticity will therefore decrease in the tape-laying industry; cooling rates will generally rise. Current temperature control systems are ignorant of these changes, which will likely induce more and more issues for the consolidation quality (Chapter 6). This creates a risky situation, as machine operators and production planners might put too much confidence into the surface temperature controls. The following section will propose alternative thermal control systems.

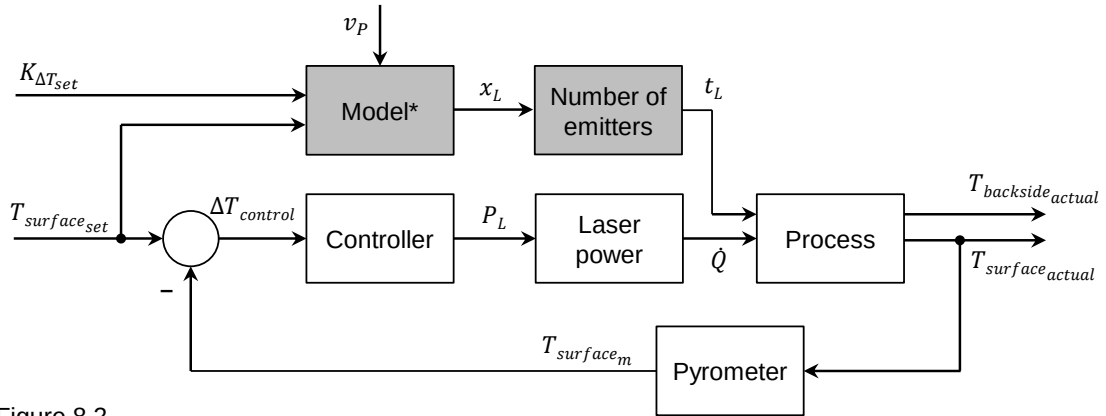
Heating Length as Additional Control Value. Previous sections showed that the irradiation length x_L could be a feasible additional control value for high-speed winding processes. By changing the irradiation length, the irradiation time changes proportionally, leading to higher (or constant) thermal penetration, yet equal surface temperatures, when the laser power is reduced accordingly (Figure 7.3). Modern laser system technologies, such as VCSEL (Section 1.6), offer systems that could be applied for this task in tape placement heads.

What is missing in the literature however, is a description on how to use the control value “irradiation length” in combination with the laser power in detail. The following sections will lay the groundwork for this.

8.1 Open-Loop Control of Temperature Gradients

Steuerung des Temperaturgradienten

Introduction. It was proposed to include the irradiation length x_L as an additional control value, to keep the surface temperature *and* the thermal penetration at constant levels. A control concept that utilizes VCSEL is presented in the subsequent figure:



*see Figure 8.2

Figure 8.1: Model-based open-loop control for simultaneous control of surface temperature and temperature gradient

Modellbasierte Steuerung zur simultanen Regelung der Oberflächentemperatur und Steuerung des Temperaturgradienten

Open-Loop Control Model. This type of control requires no further information from the process and therefore no additional sensors. However, in order to find the appropriate irradiation length x_L – and thereby the number of VCSEL emitters to be activated –, it is necessary to know the effect of the irradiation length on the temperature ratio $K_{\Delta T}$ and the surface temperature $T_{surface}$. The analytical solutions introduced in Subsection 4.3.4 and 5.1.1 can be utilized to create such a control model:

Derivation. Equation 5.1 (p. 72) provides the required surface heat flux $\dot{q}_0$ for a given tape thickness d_{tape} and irradiation time t_L . The respective laser power P_L is proportional to the surface heat flux and irradiated area (Equation 2.3). At the top of Figure 8.2, this correlation is depicted for several final surface temperatures $T_{surface_{final}}$ from 100°C to 600°C in 50°C steps (red curves).

It can be observed how different settings of surface heat flux $\dot{q}_0$ and irradiation time t_L lead to equal surface temperatures, while simultaneously, the temperature gradient changes, represented by the temperature ratio $K_{\Delta T}$, the factor between the backside temperature $T_{backside_{final}}$ and surface (front side) temperature $T_{surface_{final}}$.

Temperature Ratio. The temperature ratio $K_{\Delta T}$ depends solely on the irradiation time t_L (Equation 5.6, p. 81). The smaller $K_{\Delta T}$ the stronger the internal temperature gradient (shown in the plot by vertical grey curves). The resulting temperature ratio using state-of-the-art systems (with irradiation lengths of 40 mm) can be derived from the bottom graph.

It has to be mentioned again that $K_{\Delta T}$ is only a *practical representation* of the temperature gradient, but no direct description of the gradient's *magnitude*; a tape for example with equal $K_{\Delta T}$ exhibits flatter temperature gradients than a thin tape. Therefore, the body thickness (d_{tape}) has to be taken into account. $K_{\Delta T}$ was chosen, because it can be obtained by surface temperature measurements (Figure 5.8, p. 83).

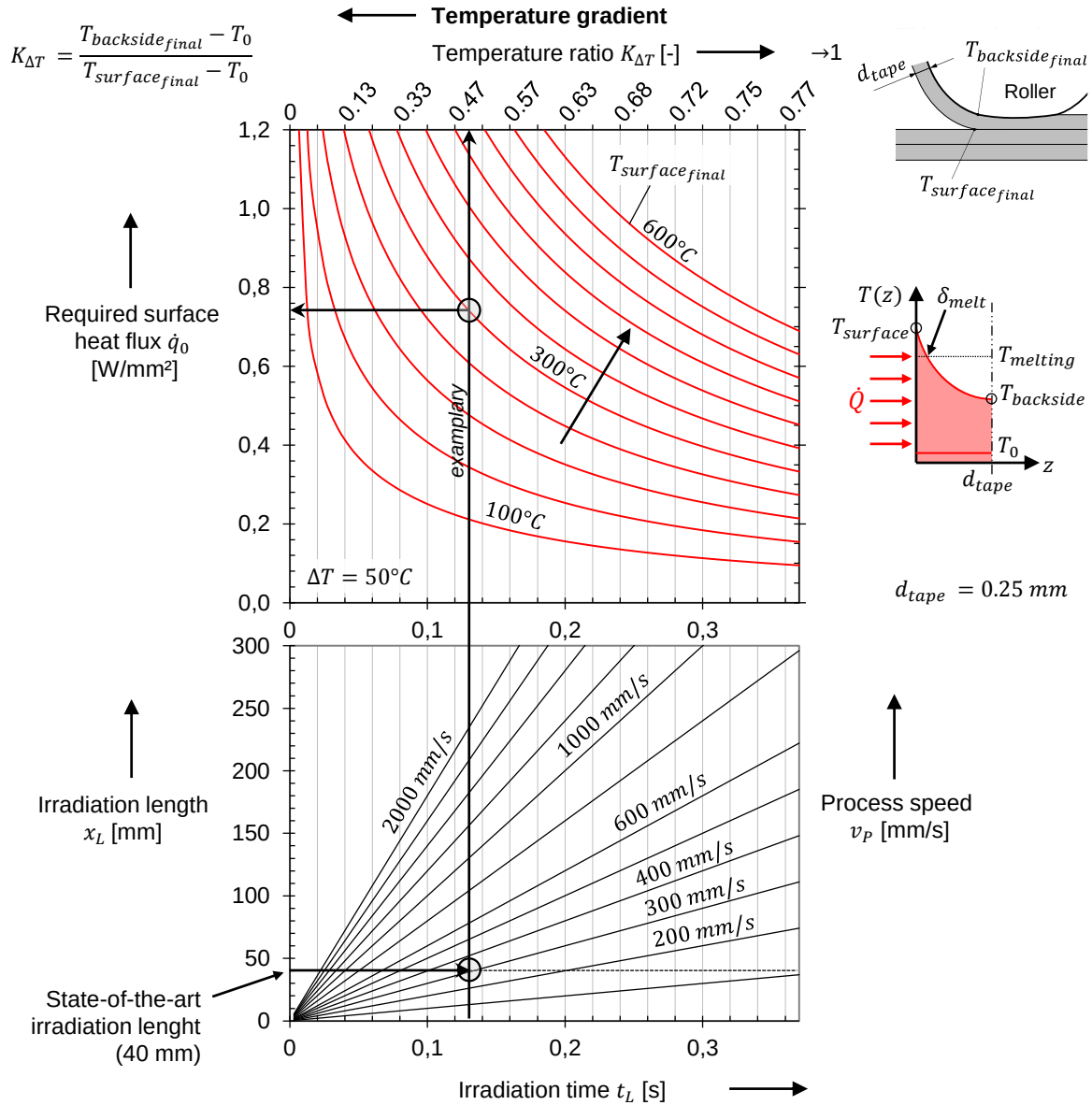


Figure 8.2: Diagram for simultaneous control of surface temperature (red curves) and thermal state of the material – temperature ratio (grey lines) – in thermoplastic tape placement of 0.25 mm-thick tapes (PEEK/CF properties)

Diagramm zu simultanen Steuerung der Oberflächentemperatur (rote Kurven) und thermischen Zustands – Temperaturverhältnis (graue Linien) – im Thermoplast-Tapelegen von 0,25 mm dicken Tapes (PEEK/CF-Eigenschaften)

At last, the linear correlation between the irradiation/heating length x_L , process speed v_p and irradiation time t_L is added at the bottom. Finally, the diagram describes how to control the surface temperature and the thermal state (via the temperature ratio) simultaneously for all process speeds.

8.2 Closed-Loop Control of Temperature Gradients

Regelung des Temperaturgradienten

A drawback of the previously proposed *open-loop* control system is its need for a model (Figure 8.2), which does not respond to changing factors automatically, e.g. material thickness tolerances $d_{tape} \pm x$ or tolerances in the thermal diffusivity $\alpha \pm y$ of the material. Figure 5.6 and Figure 5.7 showed how significant the effect of the tape thickness can be on the surface temperature development. Changing the tape material requires therefore a manual adaptation of the model, by implementing the respective properties. The (open-loop) control is also vulnerable to unknown disturbances, which can never be fully excluded.

In order to react to external disturbances and to compensate material tolerances, *closed-loop* controls are often preferred over open-loop controls. Figure 8.3 proposes such a setup for our case of controlled thermal states:

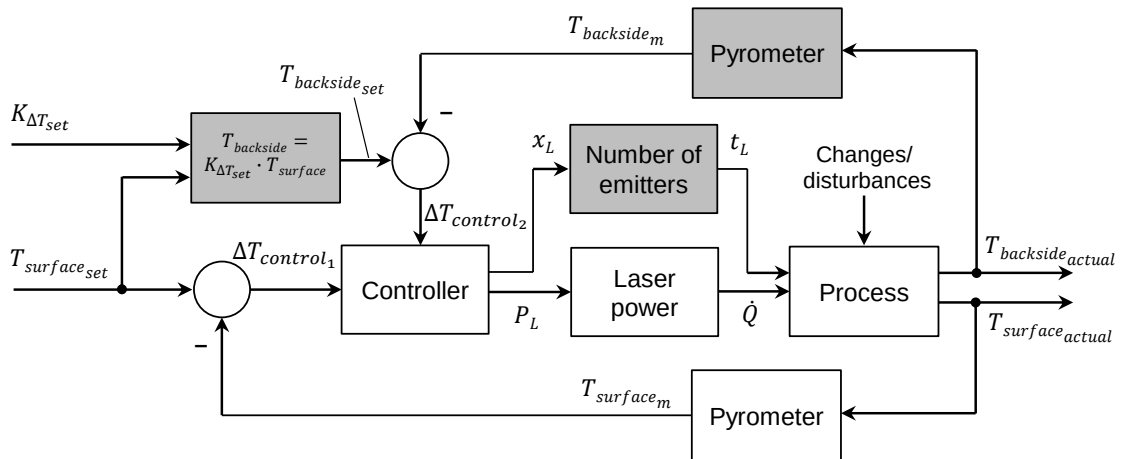


Figure 8.3: Closed-loop control for simultaneous control of surface temperature and temperature gradient

Regelung zur simultanen Steuerung der Oberflächentemperatur und des Temperaturgradienten

Such a control loop could use the information of the tape backside temperature, to gain online knowledge of the temperature ratio over the material thickness. The backside temperature can be measured by contact-free pyrometers; either during the heating cycle or shortly after the tape laydown – ideally shortly after the nip point (compare Figure 2.2, p. 16). The angle of the pyrometers vision however should be kept $> 45^\circ$.

The proposed closed-loop control is only feasible under the premise that the backside of the tape exceeds the ambient temperature (20°C). In other words: the Fourier Number has to be > 0.2 (Equation 4.17) or $\delta_{therm} > d_{tape}$ (Equation 4.10). Stronger temperature gradients are not detectable by the sensor and therefore not controllable. Measurement technologies for online information about the temperature distribution within the tape $T(z)$ is not known to the author.

8.3 Interim Conclusion

Zwischenfazit

From the diagram in Figure 8.2 some conclusions can be drawn regarding a *practical implementation* of adaptable heating lengths in tape placement systems.

Case Analysis. The presumably unproblematic case of a temperature ratio $K_{\Delta T}$ of 0.5 will be considered exemplary (top-middle of Figure 8.2) at an initial speed of 200 mm/s with an accompanying irradiation length x_L of 28 mm; $t_L = 0.14$ seconds. $\delta_{melt} \approx 40\text{--}85\text{ }\mu\text{m}$, depending on the targeted final surface temperature (Figure 5.13).

In this setting, the backside temperature is roughly half of the surface temperature ($T_{backside} \approx 0.5 \cdot T_{surface}$), leading to a moderate temperature gradient (Figure 5.2). This condition fulfills the derived requirement from Subsection 6.2.5: solid unmolten tape backside during the whole laydown process.

The initial process speed of 200 mm/s should be optimized to 2000 mm/s, to improve the output rate of the machine (pc/a). In order to keep $K_{\Delta T}$ at the same level (0.5), the irradiation length x_L has to be increased by a factor of 10, from initially 28 mm to 280 mm (compare Figure 8.2). The laser power per emitter and t_L remain equal.

System Aspects. Such long heating lengths go in the opposite direction of previous developments. The introduction of focused lasers offered several practical advantages in tape placement heads, which are in conflict such long heating lengths:

- Short heating zones are beneficial in start/stop phases. The scrap rates reported in [FORB13, p. 7, 11] are expected to increase with a use of longer heating length, especially in manufacturing of small-sized tailored blanks [BREC15].
- Short heating lengths make it possible to guide the (solid) rigid tape closely before the nip point. This can increase the laydown precision.

Winding Machines as Feasible Application. Nonetheless, *winding* processes, especially *continuous* winding processes, are not subject to these restrictions:

- *Firstly*, winding processes require only one start and one stop procedure. A single unconsolidated tape piece at the start position takes up only a fraction of the overall material per product. This keeps the cost for scrap low.
- *Secondly*, a tape guidance can be supported by appropriate tape tensioning, which is not in the same way possible in *laying* processes. In tape laying, the tape tension can peel off the tape from the substrate.
- *Thirdly*, the irradiation conditions do not change very much in tape winding, due to the lower shape complexity of the parts.
- Finally, achieving high speeds is less challenging for tape winding machines, compared to tape laying machines, due to lower acceleration forces, compare [AUTO17b] to [DOBI16].

A remaining issue of higher speeds is the declining consolidation duration t_{App} .

9 Winding Machine Concepts for a Speed-Adaptive Control of the Temperature Distribution

Wickelmaschinenkonzepte für eine geschwindigkeitsangepasste Steuerung der Temperaturverteilung

The (continuous) winding process was found to be the most feasible application case for speed-adaptive (and longer) irradiation lengths (Table 7.1). The following section will propose concepts for winding machine setups. The concepts are based on the correlation given in Figure 8.2. Two laser systems technologies will be proposed to be applied: Vertical-Cavity Surface-Emitting Laser (VCSEL) in Section 9.1 and diode lasers with an electromechanical zoom homogenizer in Section 9.2.

9.1 Winding Machine Concept with VCSEL

Wickelmaschinenkonzept mit VCSEL

VCSELs enable an adaptation of the heating length by independently controllable emitter blocks (Subsection 2.1.4). The emitter blocks are stacked in a parallel configuration, which creates adjustable long heating zones with high overall power. Currently, VCSEL technology offers laser intensities of $\approx 1.2 \text{ W/mm}^2$ (in the near field). [MOEN15] Figure 8.2 demonstrated that such intensities are sufficient to reach a wide range of thermal states, by appropriate setting of the heating length:

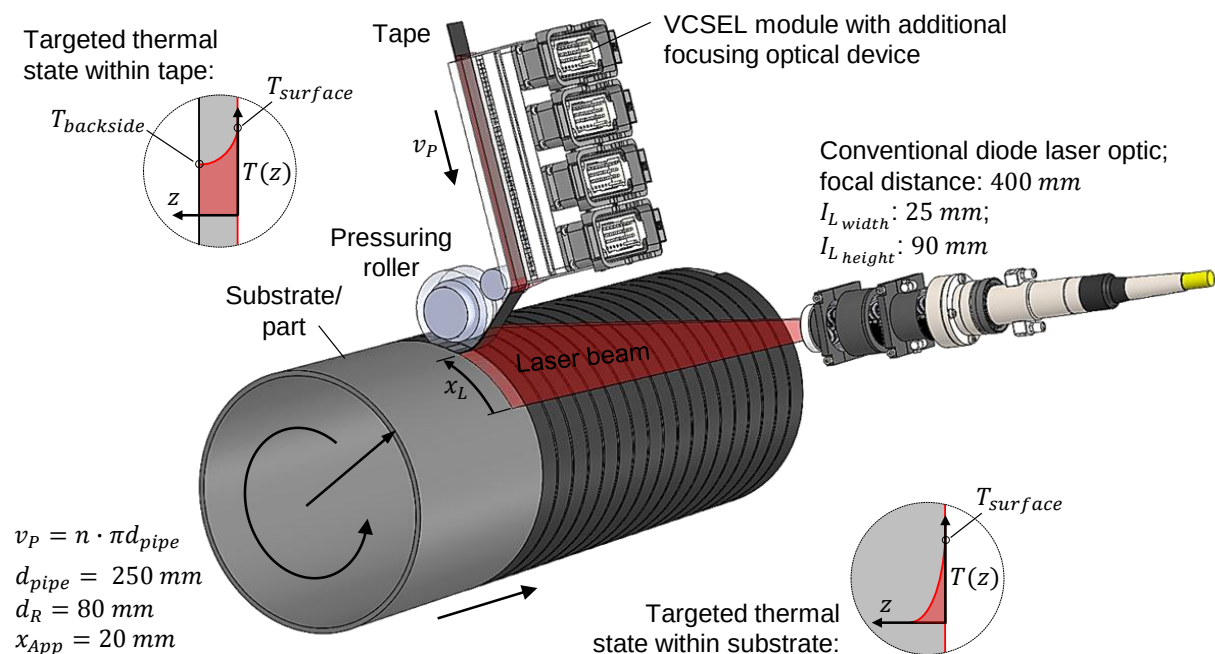


Figure 9.1: Winding machine concept with adjustable irradiation lengths for speed-adaptive control of the temperature gradient and melt pool conditions

Wickelmaschinenkonzept mit einstellbarer Bestrahlungslänge für geschwindigkeitsangepasste Steuerung des Temperaturgradienten und der Schmelzbadzustände

A wider distance of the VCSEL, relative to the target surface, reduces the maximum heat flux $\dot{q}_0$, due to the divergence angle of 20° [WEIL16b]. Therefore, it is proposed to use a focusing optic at the VCSEL beam exit, to guide the available power onto the 25 mm-wide tape (compare Figure 2.5, p. 19). The optic element increases the laser intensity from 1.2 W/mm^2 to $\approx 1.8 \text{ W/mm}^2$ and reduces heat losses left and right from the tape. Without such an element, the irradiation could lead to the heating of peripherals and the roller or would have to be shielded by a laser absorption plate.

The VCSEL is supplemented with a focused diode laser, using a fixed homogenizer. The advantage of such a separated setup is the *independent irradiation* of tape and substrate, which enables customized asymmetrical heating of tape and substrate, both in terms of final surface temperature as well as thermal penetration. The heat accumulation effect within the tape can be fully utilized, for controlled melt pool depths /lengths/times and cooling rates (Figure 9.1, top-left); the substrate can be heated with high temperature gradients for minimized heat losses to its core (bottom-right).

A (general) issue of longer irradiation lengths is the projection of the laser beam onto a *curved* substrate geometry, which creates an inhomogeneous heat flux profile $\dot{q}_0(x,y)$, especially at high winding angles and small diameters [WEIL16a, p. 2]. However, for the depicted near- 90° winding, this issue is not significant.

The tape infeed angle in the setup is $+100^\circ$ and changes to $+60^\circ$ (measured from the orthogonal plane of the consolidation force vector) by use of a deflection roller. Thereby, the VCSEL can be tilted away from the nip point area, to open up this space for the diode laser beam to enter the nip point zone. Otherwise, the electrical connectors of the VCSEL would conceal that space. The setup enables contact-free temperature measurement of the nip point region. It is proposed to realize the mechanical transmission from a pneumatic cylinder to the pressuring roller by a *lever arm*, to avoid collisions with the tape or VCSEL (not depicted in the figure). The subsequent table summarizes the machine concept by its key figures.

Table 9.1: Summarized attributes of the machine concept with VCSEL in combination with a diode laser with fixed homogenizer optic

Zusammengefasste Eigenschaften des Maschinenkonzepts mit VCSEL in Kombination mit einem Diodenlaser mit fixer Homogenisatoroptik

Attribute	Description	
Partial laser systems	VCSEL for tape preheating	Diode laser + fixed homogenizer for substrate/ final tape surface heating
Power P_L	9600 W (> with higher lengths)	Scenario: 5 kW (up to 30 kW)
Irradiation length x_L	On tape: 5-225 mm	On tape: 42.5 mm On substrate: 80 mm
Max. laser intensity I_L^*	1.8 W/mm^2	$1.6\text{-}9.8 \text{ W/mm}^2$

*considering a tape width of 25 mm

9.2 Winding Machine Concept with Zoom Homogenizer Optic

Wickelmaschinenkonzept mit Zoomhomogenisatoroptik

The second identified *adaptable* laser technology is a diode laser in combination with an electromechanical zoom homogenizer. The zoom homogenizer is equipped with a set of adjustable optics (compare Figure 2.4, p. 18, right-hand side). The irradiated field can be changed over time and space, conventionally in the form of a rectangular, projected onto a plane [LASE13b]. The response time from minimum to maximum irradiation length is roughly 1 second. In this concept, the homogenizer is positioned perpendicular to the tape plane, thereby enabling low incidence angles on the tape and substrate, for a high absorption and maximum optical penetration close to the nip point, please see Figure 9.2 and Figure 2.3 (p. 17).

Another advantage of this system setup is the accessibility for contact-free temperature measurements again, e.g. pyrometers or thermal cameras. Spatial information of the thermal condition is important to realize closed-loop controls and to monitor the process. The described strategy of maximized surface temperature close to the degradation temperature (Section 7.1) requires a precise temperature monitoring.

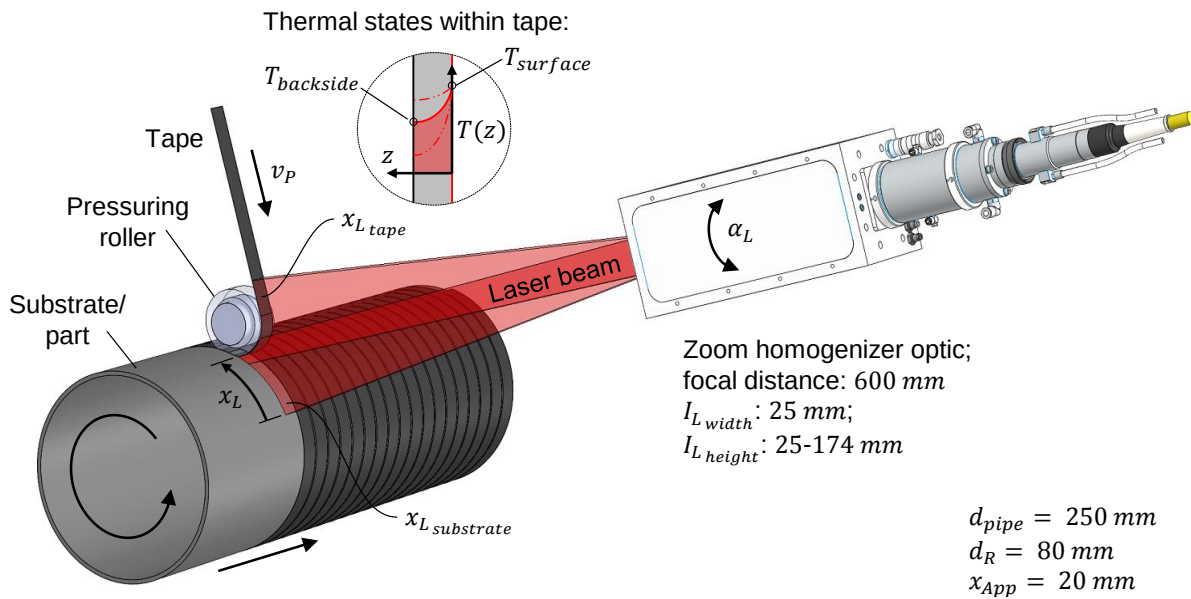


Figure 9.2: Winding machine concept with adjustable irradiation lengths for speed-adaptive control of the temperature gradient and melt pool conditions

Wickelmaschinenkonzept mit einstellbarer Bestrahlungslänge für geschwindigkeitsangepasste Steuerung der Temperaturgradienten und Schmelzbadzustände

A drawback of such a system would be the use of only 1 beam source for both tape and substrate: In order to control tape and substrate independently, the laser optic would have to be tilted and the laser power reduced (or increased) accordingly. This is indicated by the tilting arrow in the figure (the mechanics are not depicted). This intertwining of control values (P_L , α_L) however is supposed to create challenges for the control stability, like in [KOEL08].

The use of 2 separate zoom homogenizers for tape and substrate is thinkable, but increases the capital investment. Changing the irradiation length of tape and substrate independently would require a synchronous change of the irradiation angles of the two optics, which would increase the system complexity significantly.

As for the VCSEL-assisted system, a drawback of long irradiation is the projection of the laser beam onto *curved* substrate surfaces. Standard zoom homogenizers create a homogeneous irradiation in the shape of a rectangular projected onto a plane (please compare Figure 2.4, p. 18, again). Tailoring the laser beam to the specific (curved) surface would require special-purpose optical designs of the homogenizer and would be customized for only one winding diameter (and one winding angle). The system would be applicable for only one product.

The key figures of the system are summarized in the subsequent table:

Table 9.2: Summarized attributes of the machine concept with electromechanical zoom homogenizer

Zusammengefasste Eigenschaften des Maschinenkonzepts mit elektro-mechanischer Zoomhomogenisatoroptik

Attribute	Description
Power P_L	Scenario: 10 kW (up to 30 kW) 5 kW for the substrate; 5 kW for the tape
Irradiation length x_L	50/50% tape/substrate, in initial position (without tilting of the optic) 20-100 mm (can be extended by special-purpose optic design)
Max. laser intensity I_L^*	16 W/mm ²

*considering a tape width of 25 mm

Interim Conclusion

In conclusion, no off-the-shelf laser system technology exists today, which would solve all demands of a thermoplastic tapes processing at varying speeds, yet constant thermal conditions. The following developments are supposed to improve the situation:

- Micro collimation in VCSEL, for more distant positioning, leading to better access to the process zone for temperature measurement (and less risk of laser contamination). Various approaches are pursued in this field of development, e.g. [COX00] [LEVA08] [MOEN16, p. 15].
- Higher irradiation flexibility in electromechanical zoom homogenizers

In both scenarios, the irradiation left and right from the tape has to be addressed, as a non-overlapping laser beam will be difficult to realize. The projection onto curved substrates is an issue which still has to be addressed as well.

10 Optimization Strategy for the Melt Dwell Length

Optimierungsstrategie für die Schmelzbadverbleiblänge

It was shown how the melt dwell time decreases at higher speeds (Figure 5.15) and how this effect can be compensated by adaptive irradiation lengths (Figure 8.2). Developments in laser system technologies will certainly make such a process control possible in the future. However, a question that remains is what could be an *optimization target* for the irradiation length, to enable maximum bonding strengths at maximized process speeds, while avoiding negative effects of excessive heating. Such an optimization target will be derived and presented in this chapter.

Maximizing Intimate Surface Contact. From analysis of the bonding mechanisms in Subsection 6.1.2, it seems that the development of an intimate surface contact (Equation 6.1) is the prevailing limiting factor in laser-assisted tape placement – besides the special effects shown in Section 6.2. GROUVE found that intimate surface contact requires 2 decimal powers more time than autohesion for PPS/CF (for PEEK, compare Figure 6.2 and Figure 6.3). Intimate surface contact is therefore chosen as the target for the hypothetical optimization. (Other possible optimization targets could be the state of crystallinity, which correlates inversely with the cooling rate (Figure 6.6, p. 108) or the minimization of temperature-induced warpage.)

Restrictions. From analysis of the intimate surface contact model $D_{IC}(T, t)$, Equation 6.1 (p. 100), it appears that both the surface temperature $T_{surface}$ and the thermal penetration δ_{therm} should be increased as much as possible, to reach lowest through-thickness viscosities $\mu_0(z)$ and longest melt dwell times t_{melt} (/depths δ_{melt}). However, as Table 14.1 in the Appendix indicates, several disadvantages come with *unnecessary* high heat soak, e.g. thermal load on the pressuring roller, void rebound / tape deconsolidation after release of consolidation pressure or lower energy efficiency. *In-situ* tape placement as a process *strategy* tries to avoid these effects.

Final Optimization Target. Instead of simply maximizing the heat input, the irradiation should be adapted in such a way, so that the melt pool resides as long as the tape is pressurized by the consolidation roller $\Rightarrow t_{melt} = t_{App}$, – irrespective of the specific attributes of the polymer ($\mu_0(T)$, R^*) and the absolute consolidation pressure P_{App} . The pressuring time t_{App} is a function of the available pressuring length x_{App} (Equation 6.2).

The final optimization strategy is to create *sufficiently deep melt pools and moderate temperature gradients, which lead to a solidification of the melt pool just at the end of the available pressuring field*. Creating even longer melt pools seems counterproductive, as it would only lead to unnecessary high energy input, risk of void rebound / tape deconsolidation and higher thermal load on the consolidation roller. In an ideal configuration, the consolidation pressure time t_{App} and the melt dwell time t_{melt} therefore overlap (measured from the nip point on, see Figure 10.1, top-right).

The proposed irradiation strategy – adaptive heating length – allows for such an optimization: Figure 10.1 shows the decreasing pressuring time t_{App} as a function of the process speed v_p for different consolidation lengths x_{App} from the literature: [SONM97b, p. 405] [LEVY12b, p. 7] [STOK14, p. 107]. The differences in x_{App} are caused by different roller materials/geometries.

The figure is supplemented by the determined melt dwell time t_{melt} from Figure 5.15 (p. 94). It can be observed that the initial melt dwell time does not “fit” any of the reported pressuring times t_{App} . (In this initial state, a consolidation pressure length x_{App} of 2.5 mm was found to be the optimum for the melt dwell time.)

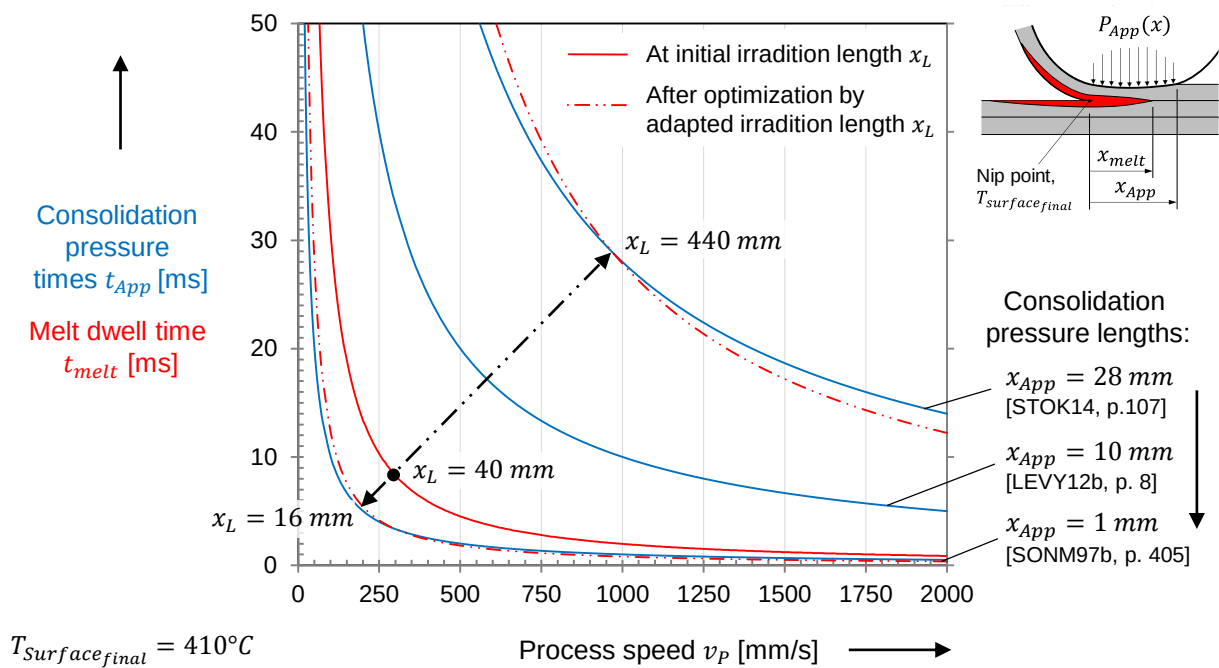


Figure 10.1: Melt pool dwell time for equal final surface temperatures and consolidation pressure time as a function of process speed. (Illustration not true to scale.)

Schmelzbadverbleibzeit bei gleicher finaler Oberflächentemperatur und Konsolidierungsdruckzeit in Abhängigkeit von der Prozessgeschwindigkeit

Optimization for Respective Consolidation Roller. However, state-of-the-art elastic rollers, made out of rubber or silicone, enable much longer pressuring lengths x_{App} in the range of 10-28 mm, so the melt pool could reside much longer for maximized degrees of intimate surface contact D_{IC} . Changing the heating length x_L by a factor of 11, from 40 mm to 440 mm (Figure 8.2), leads to an optimized condition: In this setting, the melt dwell time and the pressuring time almost *overlap*. *The melt pool solidifies just at the end of the pressuring area*. The same can be done towards shorter pressuring times (bottom-left of the figure.), to avoid unnecessary heating.

In general one can state that *it is possible to change the melt pool length via the irradiation length, according to the needs of the consolidation system*.

Changing the tape (and thereby the thermal diffusivity and thickness), or changes of the roller-substrate contact condition x_{App} , require additional adaptations of the heating length x_L . However, once the process has been optimized for $t_{App} = t_{melt}$, higher process speeds do not affect this relation very much, because both values decrease at a rate of $\approx 1/v_p$ (Figure 10.1). Further adaptations are no longer useful at this point.

From then on, the process speed v_p can (theoretically) be increased until the weld strength begins to decline. When this happens, a further increase of the process speed becomes only feasible with novel technologies for *elongated consolidation pressure lengths*. As for today, no off-the-shelf solution exists in the industry. Systems based on flexible compaction shoes have already been presented in 1992 [TOSO92, p. 122-125] and 2002 [LAMO02], but their industrial implementation is not known to the author. The sequencing of *multiple flexible* rollers (with smaller diameters) has not been tested and seems applicable in continuous winding setups (Figure 10.2, left-hand side). Another possible alternative is the development of a circulating roller cage with shorter gaps in-between the pressuring elements x_{gap} (Figure 10.2, right-hand side). This would create a long pulsating pressuring field. Winding angles below 90° would require special engineering effort, because the rollers would have to tilt along the pipe's curvature. Utilizing the tape tension for consolidation might be beneficial as well.

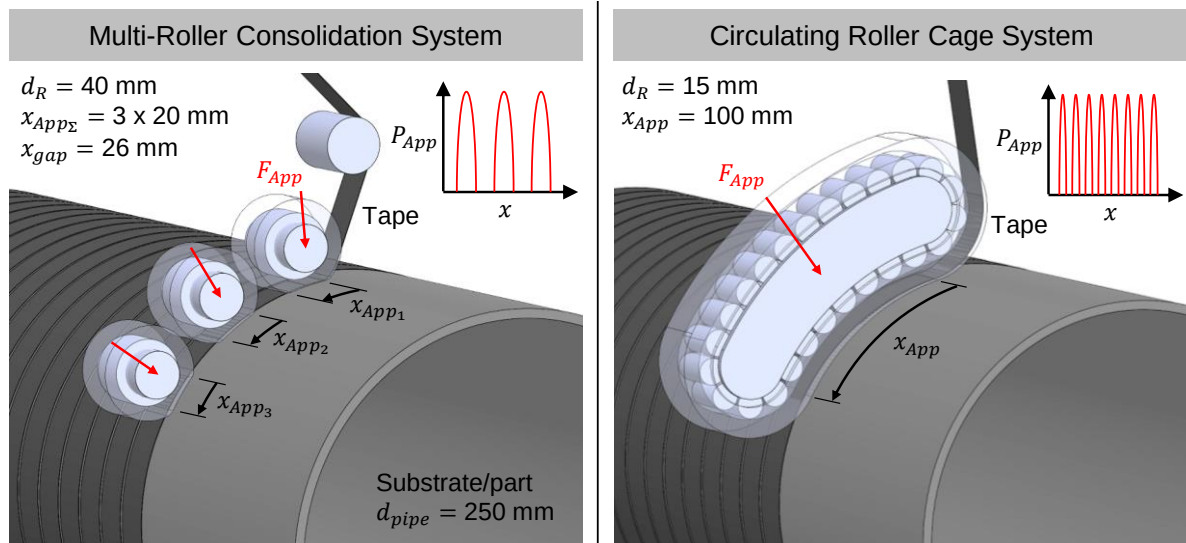


Figure 10.2: Consolidation system concepts for increased pressuring lengths (~times)
Konsolidierungssystemkonzepte für erhöhte Drucklängen (~zeiten)

Continuance of the melt pool depth and tape elasticity

Finally, what might be even more important than the overlapping of t_{App} and t_{melt} is the *continuance* of a certain melt pool depth δ_{melt} and *tape elasticity* $E(z)$. The experiments in Section 6.2 demonstrated that a certain thermal penetration supports a compensation of surface irregularities (steps). However, currently it is not known which of all mentioned conditions is more critical at high speeds: the tape elasticity $E(z)$, melt pool length x_{melt} or its depth δ_{melt} ?

11 Summary and Outlook

Zusammenfassung und Ausblick

Summary

The thesis presented models to predict the temperature development in laser-assisted thermoplastic tape placement processes. A focus was placed on the analysis of the time-dependent (transient) through-thickness temperature distribution and on processes at high speeds. Model simplifications from the literature were revised and novel simplifications were found, thereby enabling analytical solutions of the heat transfer problem – both for the heating as well as the cooling period. The simplified model was qualified on its prediction accuracy against a detailed model and was validated in experiments.

By analysis of the transient heat flow, it was found that the thinner tapes have a distinctive heating characteristic, compared to the (generally) thicker substrate: Whereas a (non-preheated) substrate passes a lot of heat to its core, the thinner tape accumulates heat, because the heat cannot flow out at the backside, due to a much higher thermal resistance to the surrounding air or roller. However, the heating characteristic of tapes and (thick) substrates converges with higher process speeds, because the time for thermal diffusion decreases with (the reciprocal of) the process speed, due to shorter heating periods; the heat accumulation effect diminishes continuously with higher speeds.

The thermal models made it possible to obtain (1) the melt pool depth (2) dwell time and length, (3) bond interface cooling rate and (4) through-thickness elastic modulus within the tape and substrate, and allowed to analyze their change at increasing process speed. The novel boundary condition considered was a well-functioning (surface) temperature control system of unlimited laser power, which laser sources on the market practically enable.

The analysis showed the following phenomena: The temperature gradient within the tape increases continuously – similar to the temperature gradient within a steak on an increasingly hot cooking plate. Thereby, the melt pool becomes thinner and the melt dwell *time* shortens. The melt dwell *lengths* does not change, because the tape also travels at higher speeds – the melt dwell length is a quasi-static variable.

The forecasted development of a thermal skin layer by GROUVE was described quantitatively. Increasing the surface temperature was found to deepen the melt pool, but the strategy is limited by the polymer's degradation temperature. The steepening gradient also leads to a "stiffening" of the tape at process speeds > 500 mm/s (for 0.25 mm-thick PEEK/CF tapes), caused by a colder core and backside.

An analysis of the known bonding mechanisms revealed that these changes will at some point inevitably begin to influence the weld strength, by affecting first the intimate surface contact development and later autohesion. Due to high uncertainties in the literature about the temperature-dependent viscosity and the temperature-dependent

reptation time, a valid prediction about a specific speed limit for in-situ consolidation was not possible yet. Instead, experiments were conducted with a novel test setup, which enables the consolidation at defined temperature gradients and tape speeds.

The experimental setup was used for an initial investigation on the general effect of temperature gradients at a consolidation speed of 1 m/s. Two (unexpected) conflicting positive effects were observed: On the one hand, the backside of the tape stays unmolten at high gradients, so it remains flat and smooth, which is expected to be beneficial for subsequent laydowns. On the other hand, the high gradients inhibit the melt flow and malleability of the tape: A surface step of 60 μm – induced by a Polyimide tape – was thick enough to prevent the filling of a 2 mm-wide area at the edge of the step change, although the original tape had a thick and smooth surface polymer layer of 25 μm . It is expected that this phenomena can induce severe issues, as surfaces exhibit cavities $> 200 \mu\text{m}$, e.g. by tape crossovers or gaps/overlaps.

Assumptions from the literature were confirmed, which state that higher speeds lead to higher bond interface cooling rates (and thereby continuously decreasing states of crystallinity). This is supposed to increase the bond interface fracture toughness.

In order to control the thermal state in the material – independently from the process speed – several irradiation strategies were investigated and compared on their usefulness and feasibility to be applied in tape placement systems. *Maximization* of the surface temperature was found to be easy to implement, but also limited, because the degradation temperature of the respective polymer sets a barrier. Changing the irradiation *distribution* promises the most benefits and widest field to control $T(z)$, but is expected to be more difficult to realize with state-of-the-art laser system technologies and heat transfer simulation tools. The most feasible strategy was found to be adaptive irradiation *lengths*, e.g. by created VCSEL or by electromechanical zoom homogenizers. The encompassing correlation between irradiation length, laser power, surface temperature and thermal penetration was described analytically.

The principle of adaptive irradiation lengths was transformed into winding machine concepts. Optimization potentials for the laser technologies were identified: whereas the VCSEL is less suited for distant positioning, which decreases the risk of contamination and increases the accessibility for contact-free temperature measurement, the (standard) zoom homogenizer requires a simultaneous tilting of the optic to enable dissimilar energy input in the tape and substrate; using multiple zoom homogenizers increases the cost of the system as well as its complexity and requires a synchronous tilting of the optic to enable irradiation close to the nip point.

Finally, a novel optimization strategy for laser-assisted tape placement processes was derived. The strategy has the goal of adjusting the melt dwell time relative to the available pressuring time of the respective consolidation roller, by changing the laser irradiation length accordingly. The pressuring lengths reported in the literature differ from 1 mm in rigid rollers up to 28 mm in elastic rollers. The irradiation length should be adaptable in similar ranges, because it was found that the pressuring time decreases with higher process speeds at a similar rate as the melt pool dwell time.

Outlook

Before realizing a tape placement head with speed-adaptive irradiation, it would be reasonable to further quantify the correlations between process speed (consequent temperature gradients), material properties (flatness, reptation time), workpiece properties (gaps/overlaps, surface appearance), system design (roller diameter/elasticity) and weld strength. Disentangling all cross correlations will require a lot more research. The proposed experimental setup could be an efficient tool for such future investigations. Winding seems to be a suitable alternative process to investigate high temperature gradients, because winding systems are capable of performing high line speeds.

Today, it is also unclear whether the pressuring length – predefined by the roller – or the irradiation length – defined by the laser beam – is the *major limiting factor* for the intimate surface contact development. In case the pressuring time is the limiting factor, more effort should be put into the development of prolonged pressuring fields. It may also be the case that some types of tape – e.g. tapes with high surface roughness – require longer pressuring lengths, while other types of tape – e.g. very flat tapes – require longer irradiation lengths. More research is required to answer this question.

Currently it appears that the irradiation length of today's tape placement heads was chosen for practical purposes, with less consideration of the actual bonding process requirements. It seems likely that adaptive irradiation technologies can improve the laydown process at conventional speeds and might also help to push the process speed limits. If this holds true, the logical next step would be to realize the proposed machine designs and test the systems for its ability to increase the weld strength at high process speeds. Tape placement machine builders would gain a distinguishing feature, as the machines would be more productive than the state of art. Winding machines appear to be the ideal application case for such an initial realization. The winding process requires only few start/stop procedures, the tape tension can be used for tape guidance and machines are already capable of line speeds > 2.5 m/s.

A clear drawback of today's VCSEL is the divergence angle, which requires close positioning of the laser next to the material, to achieve high surface heat fluxes. This sets the laser at risk of contamination. Increasing the collimation of VCSEL would be a significant improvement for their applicability in tape placement heads.

From analysis of the bonding mechanisms, it appears that the intimate surface contact development is the limiting factor for high-speed tape placement. Future improvements of the tape design could include a reduction of the polymers (zero-shear rate) viscosity, thermal diffusivity by additives and a thickening and flattening of the surface polymer.

Maximizing the surface temperature up to the degradation level leads to the benefit of minimized viscosity. However, accurate temperature control and monitoring are necessary to make this strategy feasible. It was also found that the surface temperature homogeneity deviates up to 15% along the width. It is not yet clear whether this deviation was caused by variations in thickness or fiber distribution.

Zusammenfassung

In der vorliegenden Arbeit wurden Modelle zur Beschreibung der laserunterstützten Erwärmung von faserverstärkten Thermoplastbändern vorgestellt. Der Fokus lag auf der zeitabhängigen (transienten) Temperaturentwicklung in der Dickenrichtung des Materials bei hohen Geschwindigkeiten. Modellvereinfachungen aus der Literatur wurden überarbeitet und neue Vereinfachungen wurden getroffen, wodurch analytische Lösungen des Wärmeleitungsproblems möglich wurden – sowohl für den Erwärmungs-, als auch den anfänglichen Abkühlvorgang. Das vereinfachte Modell wurde gegen ein detailliertes numerisches Modell auf seine Vorhersagegenauigkeit hin bewertet und experimentell validiert.

Durch eine Analyse der transienten Wärmeflüsse wurde herausgefunden, dass sich dünnere Tapes deutlich in ihrer Erwärmungscharakteristik von den (generell) dickeren Substraten unterscheiden: Während (nicht vorgewärmte) dicke Substrate die Wärme in die Tiefe ableiten, staut sich die Wärme in dünneren Tapes auf, da hier der Wärmeabtransport an der Rückseite zur Luft oder zur Rolle hin verhindert ist, aufgrund der deutlich höheren Wärmeübergangskoeffizienten. Hierbei ist zu beachten, dass sich die Erwärmungscharakteristik von Tapes und dicken Substraten bei hohen Geschwindigkeiten angleichen werden, weil die Zeit für die thermische Diffusion bei hohen Geschwindigkeiten (mit dem Reziprok) abnimmt, hervorgerufen durch die immer kürzer werdende Bestrahlungsdauer. Der beschriebene Wärmestau-Effekt im Tape nimmt hin zu höheren Geschwindigkeiten kontinuierlich ab.

Durch die thermischen Modelle war es möglich die folgenden Größen in Abhängigkeit zur Geschwindigkeit zu setzen: (1) Schmelzbad-Tiefe, (2) Schmelzbadverbleib-Zeit und -Länge, (3) Abkühlrate der Fügezone und (4) der Elastizitätsmodul in Dickenrichtung. Eine neue Randbedingung bei der Modellierung war hierbei die Annahme eines Lasers mit nicht limitierter Leistung – eine Randbedingung die durch neueste Laserquellen am Markt mit > 10 kW repräsentativ ist.

Die Analyse zeigte folgendes Phänomen: Der Temperaturgradient im Tape steigt kontinuierlich an, ähnlich zu dem Temperaturgradienten in einem Steak auf einer zunehmend heißen Herdplatte. Durch den steigenden Gradienten nimmt die Schmelzbad-Tiefe im Tape kontinuierlich ab und die Schmelzbadverbleib-Zeit verkürzt sich. Die Schmelzbadverbleib-Länge bleibt jedoch konstant, da sich das Tape gleichzeitig auch mit höheren Geschwindigkeiten durch die Fügezone hindurchbewegt – die Schmelzbadverbleib-Länge ist daher eine quasi-statische Größe.

Das vorhergesagte Entstehen einer dünnen thermischen Hautschicht von GROUVE konnte erstmalig quantitativ beschrieben werden. Es stellte sich heraus, dass ein Anheben der Oberflächentemperatur zwar das Schmelzbad leicht vertieft, jedoch auch, dass diese Strategie limitiert ist, durch die Degradationstemperatur des Polymers. Zudem führt der steigende Gradient zu einer „Versteifung“ des Tapes, beginnend ab Geschwindigkeiten von > 500 mm/s (für 0,25 mm dicke PEEK/CF-Tapes), hervorgerufen durch einen noch starren, kalten Kern und Rückseite.

Eine Analyse der Fügemechanismen zeigte, dass diese thermischen Veränderungen bei hohen Geschwindigkeiten irgendwann zwangsläufig auch die Fügefestigkeit beeinflussen werden, durch entweder einer Beeinflussung der makroskopischen Drapierung, des intimen Lagenkontaktes oder der Autohäsion. Aufgrund der hohen Ungewissheit in der Literatur über die temperaturabhängige Viskosität des Polymers (hier PEEK), und den temperaturabhängigen Reptationszeiten, war eine valide Aussage über ein Geschwindigkeitslimit für das in-situ Tapelegen noch nicht möglich. Stattdessen wurde ein neuer Prüfstand entwickelt, welcher das Fügen von Tapes mit definierten Temperaturgradienten bei definierten Geschwindigkeiten ermöglicht.

Der Prüfstand wurde dazu genutzt, um eine erste Untersuchung zum generellen Einfluss des Temperaturgradienten bei Konsolidierungsgeschwindigkeiten von 1 m/s durchzuführen. Zwei (unerwartete) im Konflikt stehende positive Effekte wurden beobachtet: Auf der einen Seite bleibt das Tape bei hohen Temperaturgradienten auf der Rückseite im festen Zustand, was sehr wahrscheinlich positiv für nachfolgende Konsolidierungsprozesse ist, aufgrund der geringen Rauigkeit und weil die elastische Rolle thermisch geschont wird. Auf der anderen Seite verringert ein hoher Temperaturgradient das verfügbare Schmelzbad und die Formbarkeit des Tapes nimmt ab: Ein Dickensprung auf der Oberfläche von 60 μm – induziert durch ein Polyimid-Tape – reichte aus, um das Füllen einer 2 mm breiten Zone am Rand des Dickensprungs zu verhindern. Es ist zu erwarten, dass dieses Phänomen sich entscheidend auf die Bauteileigenschaften auswirkt, da Tape gelegte Oberflächen i.d.R. Kavitäten von $> 200 \mu\text{m}$ aufweisen, bspw. an Tape-Kreuzungspunkten oder -Überlappungen/-Lücken.

Annahmen aus der Literatur zu einer ansteigenden Kristallinität in der Fügezone (hervorgerufen durch hohe Geschwindigkeiten/ hohe Gradienten) konnten bestätigt werden. Es wird daher erwartet, dass hohe Geschwindigkeiten/ hohe Gradienten die Bruchzähigkeit der Fügezone stetig erhöhen.

Um den thermischen Zustand im Material maschinell zu steuern – unabhängig von der Prozessgeschwindigkeit – wurden verschiedene Bestrahlungsstrategien betrachtet und auf deren Nutzbarkeit und Einsetzbarkeit in Tapelegesystemen hin verglichen: Eine *Maximierung* der Oberflächentemperatur stellt sich als einfachstes Instrument heraus, welches jedoch durch die Degradationstemperatur des Polymers limitiert ist. Eine Veränderung der *Bestrahlungsverteilung* verspricht das größte Spektrum um die Wärmeverteilung in Dickenrichtung zu beeinflussen, ist jedoch schwierig zu realisieren mit Lasern des Stands der Technik und den heutigen (nicht inversen) Simulationswerkzeugen der Wärmeleitung. Als vielversprechende mittelfristige Strategie lässt sich die Anpassung der *Bestrahlungslänge* nennen, bspw. durch VCSEL oder elektromechanische Zoomhomogenisatoroptiken. Der zu deren Nutzung relevante Zusammenhang zwischen Bestrahlungslänge, Laserleistung, Oberflächentemperatur und thermischer Eindringtiefe wurde durch analytische Lösungen beschrieben und visualisiert.

Das Prinzip der adaptiven Bestrahlungslänge wurde in zwei Konzepte für das Wickeln überführt. Optimierungspotentiale für die entsprechenden Lasertechnologien wurden identifiziert: Während VCSEL wenig geeignet sind für eine weit entfernte Positionierung, welche den Schutz des Lasers erhöhen würde, und den Zugang für optische berührungslose Messtechnik verbessert, erfordert die Nutzung von Zoomhomogenisatoroptiken ein simultanes Neigen der Optik, um eine gezielt ungleichmäßige Bestrahlung von Tape und Substrat zu ermöglichen. Die Nutzung von zwei Zoomhomogenisatoroptiken stellt eine weitere Alternative dar, erhöht jedoch die Kosten und die Komplexität des Gesamtsystems.

Zum Schluss wurde eine neue Optimierungsstrategie für laserunterstützte Tapelegeprozesse abgeleitet. Bei dieser Strategie wird versucht, die Schmelzbadverbleib-Zeit relativ zu der verfügbaren Druckzeit der Konsolidierungsrolle anzupassen, durch eine entsprechende Anpassung der Bestrahlungslänge. Die in der Literatur dokumentierten Drucklängen liegen zwischen 1 mm für starre Rollen und 28 für elastische Rollen. Die Bestrahlungslänge sollte daher in ähnlichen Größenordnungen anpassbar sein, da sich zeigt, dass die *Druckzeit bei höheren Prozessgeschwindigkeit in ähnlicher Art und Weise abnimmt wie die Schmelzbadverbleib-Zeit*.

Ausblick

Bevor ein Tapelegekopf mit geschwindigkeitsangepasster Bestrahlungslänge realisiert werden kann müssen weitere Untersuchungen durchgeführt werden, um die Korrelation zwischen den nachfolgenden Größen zu ermitteln: Prozessgeschwindigkeit (~ Temperaturgradient), Materialeigenschaften (Rauigkeit, Reptationszeit), Bauteileigenschaften (Lücken/Überlappungen, Oberfläche), Konstruktion (Andruckrollen-Durchmesser/-Elastizität) und erzeugter Fügefestigkeit. Die Entwirrung aller möglicher Kreuzkorrelationen erfordert einige weitere Forschungsarbeiten. Der vorgestellte Prüfstand könnte als effizientes Werkzeug für solche Untersuchungen dienen. Auch der Prozess des Wickelns erscheint sehr geeignet, um den Einfluss von Temperaturgradienten zu untersuchen, aufgrund der einfach erreichbaren hohen Geschwindigkeiten.

Zudem ist bislang unklar, ob die limitierte *Drucklänge* – vorbestimmt durch die Andruckrolle – oder ob die *Bestrahlungslänge* des Lasers die limitierenden Faktoren für die Ausbildung des intimen Lagenkontakts sind. Sollte die Druckzeit der limitierende Faktor sein, sind weitere Anstrengungen zur Erhöhung der Druckzeit notwendig. Es könnte durchaus sein, dass einige Tapesorten – bspw. solche mit hohen Rauigkeiten – ein längeres Druckfeld erfordern, während andere Tapesorten – bspw. sehr glatte dicke Tapes – längere Bestrahlungszeiten benötigen. Weitere Forschung ist notwendig, um diese Frage zu beantworten.

Zurzeit erscheint es so, dass die heutigen Bestrahlungslängen in Tapelegeköpfen rein aus praktischen Gründen ausgewählt wurden, ohne detaillierte Berücksichtigung des thermischen Zustands in der Dickenrichtung. Möglicherweise könnten daher erhöhte

Bestrahlungslängen die Verfahrensgrenzen des Tapelegens verschieben. Sollte dies der Falls ein, wäre der nächste Schritt ein gezieltes Redesign der Maschinen mit anschließender Untersuchung der erreichbaren Fügefestigkeiten bei hohen Geschwindigkeiten. Hersteller von Tapelegeanlagen könnten sich hierdurch ein Alleinstellungsmerkmal erarbeiten, weil Systeme mit längeren Bestrahlungslängen höhere Verarbeitungsgeschwindigkeiten ermöglichen und somit produktiver wären als Maschinen des Stands der Technik. Insbesondere Wickelmaschinen erscheinen hier ein prädestinierter Anwendungsfall zu sein, denn das Wickeln erfordert i.d.R. weniger Start/Stopp-Prozesse, die Tapespannung kann zur Tapeführung genutzt werden und heutige Maschinen erreichen bereits Wickelgeschwindigkeiten von $> 2,5$ m/s.

Ein klarer Nachteil heutiger VCSEL ist deren Divergenzwinkel, welcher eine nahe Positionierung des Lasers zum Material hin notwendig macht, um hohe Bestrahlungsintensitäten zu erreichen. Dieser Umstand setzt die Heizquelle in Gefahr verunreinigt zu werden. Eine bessere Kollimation heutiger VCSEL, bspw. auf der Ebene der Mikrolaser, würde diesen Umstand deutlich verbessern und deren Nutzung in Tapelegeköpfen weiter vorantreiben.

Aus der Analyse der Fügemechanismen lässt sich schließen, dass der intime Lagenkontakt der primäre limitierende Faktor für das Hochgeschwindigkeitstapelegen ist. Folgende zukünftige Verbesserungen der Tapegegestalt könnten deren Verarbeitung mit hohen Geschwindigkeiten verbessern: eine Reduzierung der Polymerviskosität, eine Erhöhung der Wärmeleitfähigkeit durch Additive sowie eine Aufdickung und Abflachung der Polymeroberfläche.

Die beschriebene Strategie der Maximierung der Oberflächentemperatur bis hin zur Degradationstemperatur hat den Vorteil minimierter Viskosität, erfordert jedoch eine sehr präzise Regelung und Überwachung. Versuche haben gezeigt, dass die Homogenität der Oberflächentemperatur jedoch um bis zu 15% über der Tapebreite schwankt. Es ist noch nicht klar, ob diese Abweichung durch eine Variation der Tapedicke oder durch eine inhomogene Faserdichteverteilung verursacht wird.

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Prepublications

Vorveröffentlichungen

- [WEIL16a] Weiler, T.; Emonts, M.; Janssen, H.: *On the use of flexible intensity distributions for thermoplastic tape placement by means of vertical-cavity surface-emitting laser (VCSEL)*. 3rd ITHEC, Bremen, Germany, 2016
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13 Appendix I: Method of Mirroring Heat Sources

Anhang I: Methode der Spiegelquellen

The *Method of Mirroring Heat Sources* is valid under the assumption that heat is quasi-reflected at the backside and the front side of a body, due to significantly higher thermal resistances out of the body R_{out} compared to the internal thermal resistance R_{within} by conduction ($R_{out} \gg R_{within}$), given that heat reaches the back of the body ($d < \delta_{therm}$). These conditions were found to apply for the heating of tapes (Figure 4.6 and Figure 4.7, p. 55, 57)

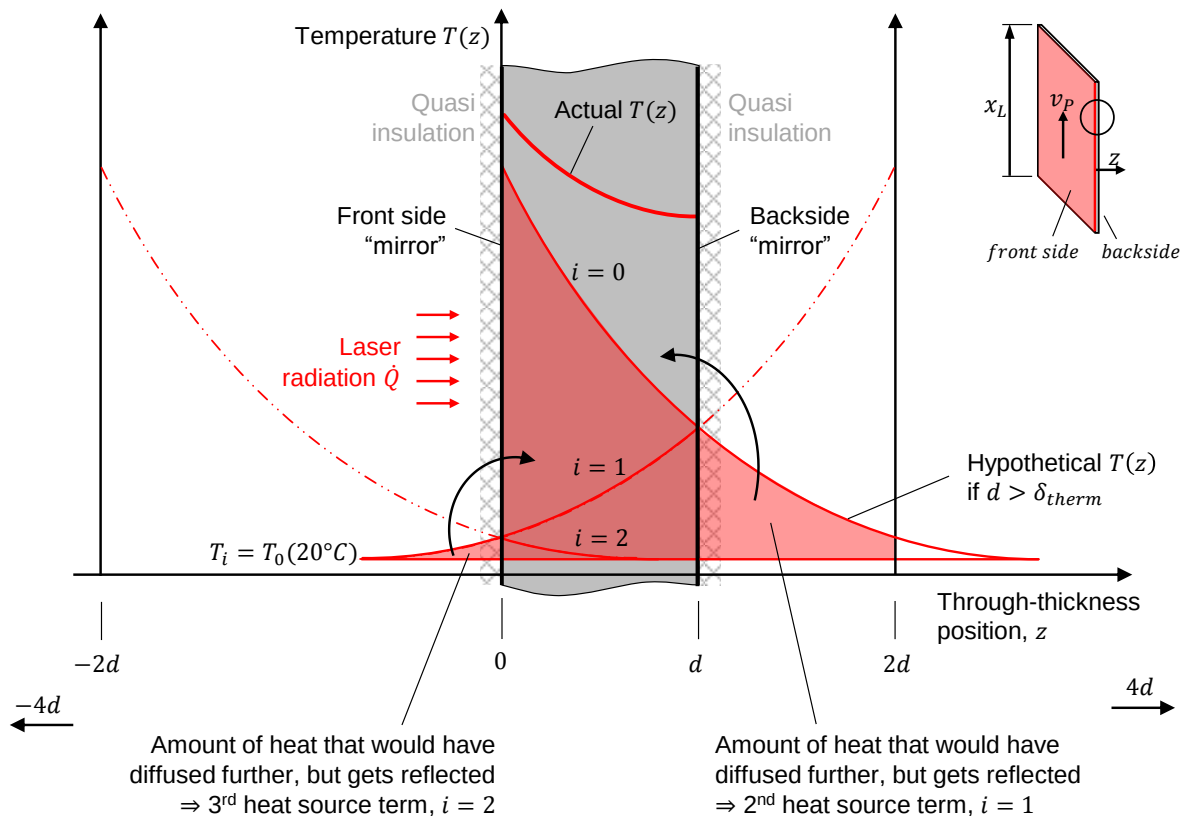


Figure 13.1: Visualization of the Method of Mirroring Heat Sources for determination of temperature distributions in finite bodies. Adapted from [POPR05, p. 55-56]. Please consider in combination with Figure 4.6 and Figure 4.7, p. 55, 57

Visualisierung der Methode der Spiegelquellen zur Ermittlung der Temperaturverteilung in endlich dicken Körpern. Bitte betrachten Sie mit Abb. 4.5, 4.7

The assumption of "reflected heat" leads mathematically to further heat source terms, which have to be summed up. The temperature distribution $T(z)$ results from the sum of all occurring mirrored heat sources (Equation 4.19). The number of sums depends on the thermal penetration depth δ_{therm} (Equation 4.10) and the body thickness d . The higher the thermal penetration, and the thinner the body, the more heat sources are required to calculate $T(z)$ precisely. It was found that the *Method of Mirroring Heat Sources* can be applied for the *cooling phase* of finite bodies as well (Equation 4.24).

14 Appendix II: Pros and Cons of Increasing Temperature Gradients

Anhang II: Vor- und Nachteile steigender thermischer Gradienten

Table 14.1: Listing of the identified pros and cons of increasing temperature gradients in through-thickness direction

Auflistung der identifizierten Vor- und Nachteile steigender thermischer Gradienten in Dickenrichtung

Affected aspects	Temperature gradients ↑ / heat soak ↓	
	Eval.	Reason
Degree of autohesion D_{Ah}	–	Higher cooling rates lead to decreasing time periods the bond interface remains at elevated temperatures
Degree of intimate surface contact D_{IC}	–	Thinner melt pool, shorter melt dwell length and increased tape rigidity
Repetitive consolidation / post healing	–	Lower thermal penetration prevents heat to reach previous subjacent bond interfaces
Roller durability	+	Lower thermal load; less risk of matrix adherence
Crystallinity in bond interface	–	Lower crystallinity, due to higher (local) cooling rates in the bond interface
Crystallinity in final part	–/+	Lower crystallinity, due to higher (global) cooling rates; avoidance of part heating $< T_{recrystallization}$
Laminate surface appearance (flatness)	+	Less deformation of the (initially flat/smooth) tape backside; less deformation of the tape
Release of volatiles	+	Release of volatiles is inhibited by local heating
Voids	–/+	Less void rebound (void growth) after consolidation pressure is released, assuming void-free tapes; however poorly impregnated tapes are less consolidated
Deconsolidation	+	Less risk of deconsolidation by tape tension after consolidation pressure is released
Local stresses in bond interface	–/+	Higher thermal stresses near the bond interface, due to higher temperature gradients; however, lower volumetric shrinkage in case of semi-crystalline matrices
Global stresses in laminate	+	Less <i>global</i> thermal stresses/warpage due to lower overall heat input
Formability	–	Higher rigidity; reduced tape plasticity/malleability
Dimensional stability of thin substrates	+	Thin substrates remain more rigid, due to lower thermal penetration; e.g. laydown on thin liners (e.g. tank)
Tape steering	–	Higher elastic modulus in thickness direction inhibits shear straining in fiber direction
Gaps/overlaps	+	Higher through-thickness viscosity inhibits tape widening
Output per capital investment (€/kg/hr)	+	High-power lasers tend to be more cost-efficient than low-power lasers, in terms of laydown rate per investment
Energy efficiency	+	Lower heat input required to reach desired $T_{surface}$
Weld strength τ_{weld}	–/+	Depends on a multitude of the aforementioned aspects and specific machine setup / tape properties
Fracture toughness	–/+	Depends on a multitude of the aforementioned aspects and specific machine setup / tape properties

“+”: positive impact; “–”: negative impact

15 Appendix III: Experimental Setups

Anhang III: Messaufbauten

15.1 Experimental Setup for Measurement of Temperature Gradients

Versuchsaufbau zur Messung von Temperaturgradienten

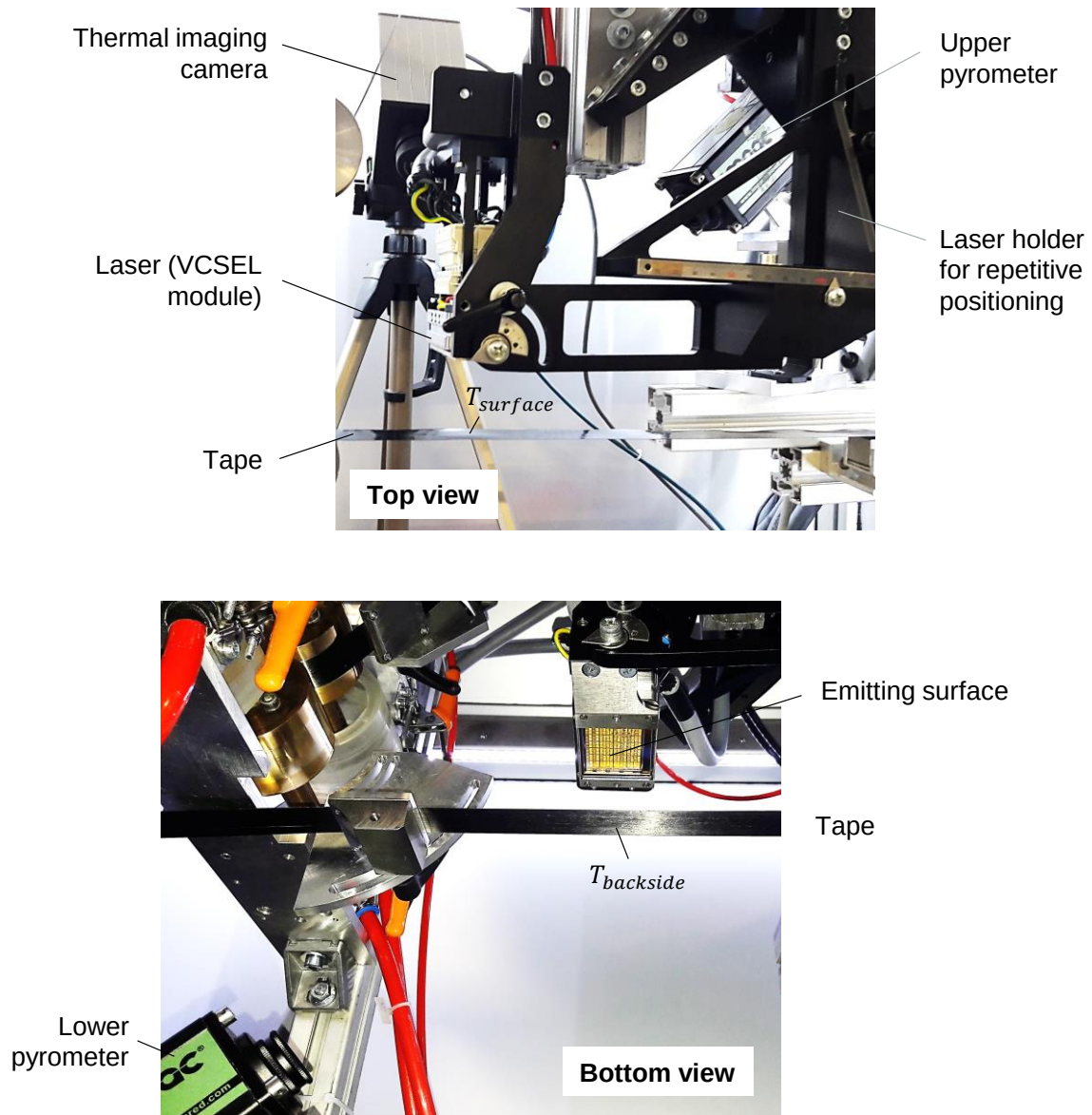


Figure 15.1: Experimental setup for measurement of temperature gradients

Versuchsaufbau zur Messung von Temperaturgradienten

15.2 Magnification of the Pull-Through Test

Vergrößerung des Durchzugversuchs

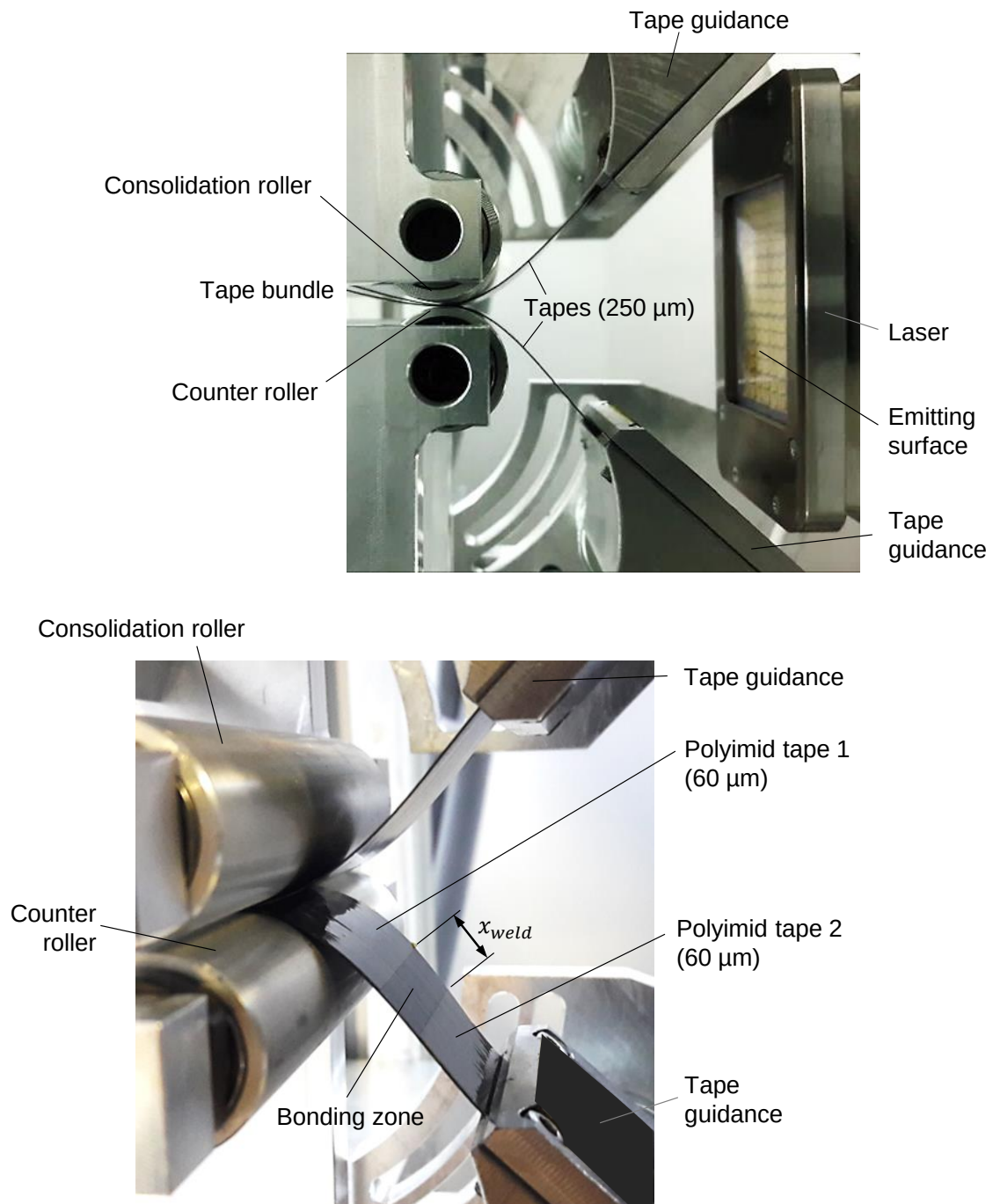


Figure 15.2: Pull-through test for the bonding of tapes with various temperature gradients at defined process parameters (process speed and consolidation pressure)

Durchzugversuch zum Fügen von Tapes mit verschiedenen Temperaturgradienten bei definierten Prozessbedingungen (Prozessgeschwindigkeit und Konsolidierungsdruck)

15.3 Lap Shear Test Setup

Aufbau des Zugscherversuchs

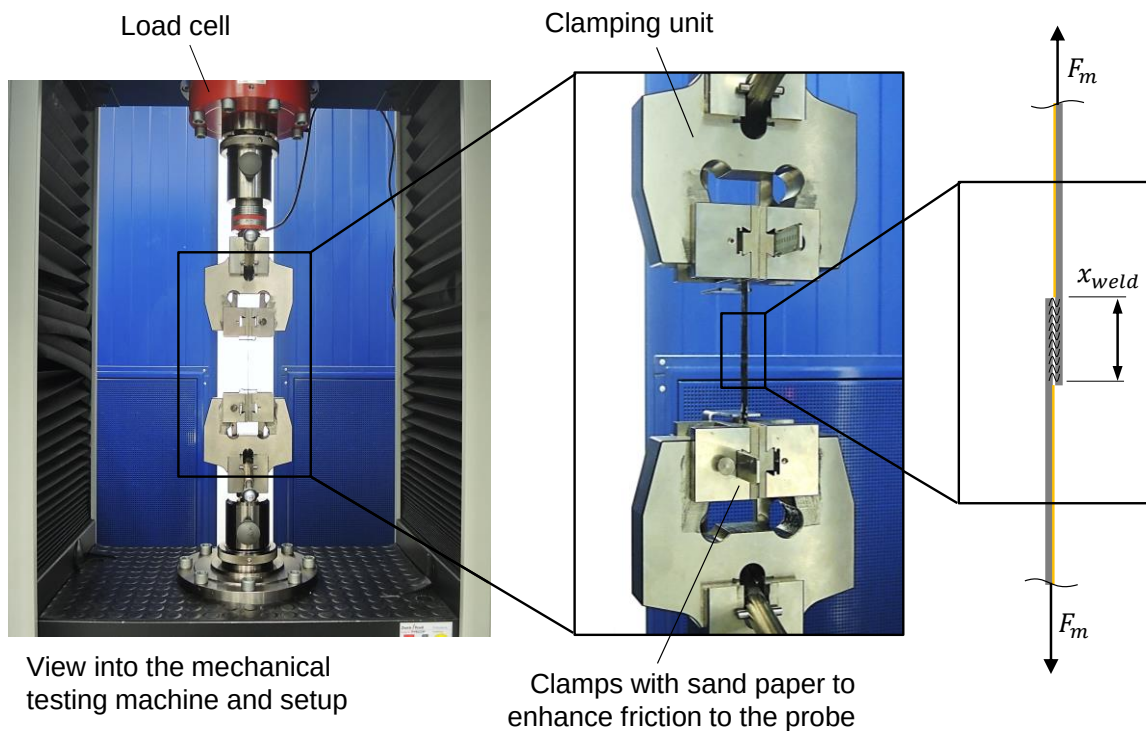


Figure 15.3: Lap shear test setup for the determination of weld strengths

Aufbau des Zugscherversuchs zur Ermittlung der Fügefestigkeiten

15.4 Reference Probe

Referenzprobe

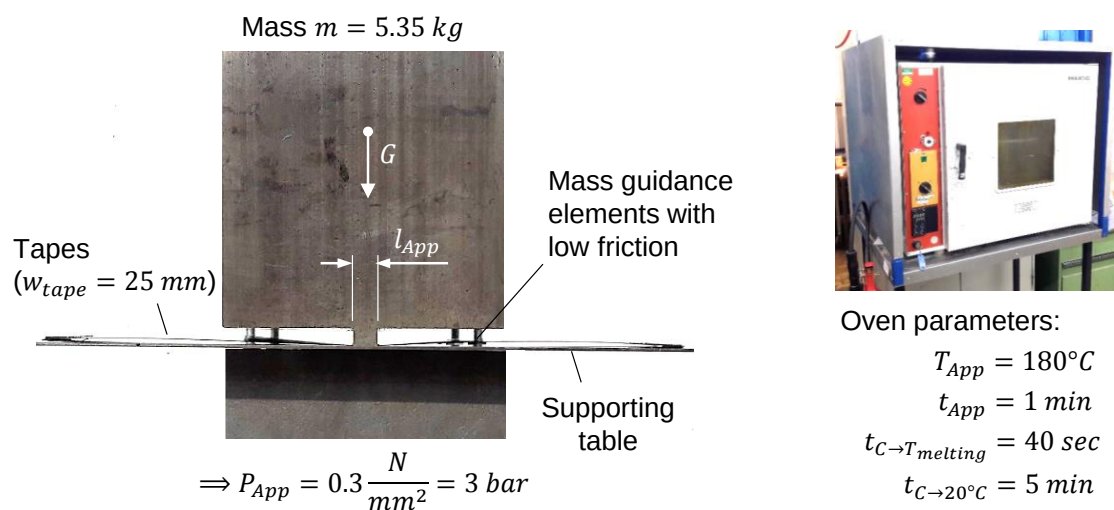


Figure 15.4: Preparation of the consolidation process for the reference probe

Vorbereitung des Konsolidierungsprozesses für die Referenzprobe

16 Appendix IV: Preliminary Investigations

Anhang IV: Voruntersuchungen

16.1 Preliminary Investigation on Surface Irradiation Homogeneity

Voruntersuchung zur Homogenität der Oberflächenbestrahlung

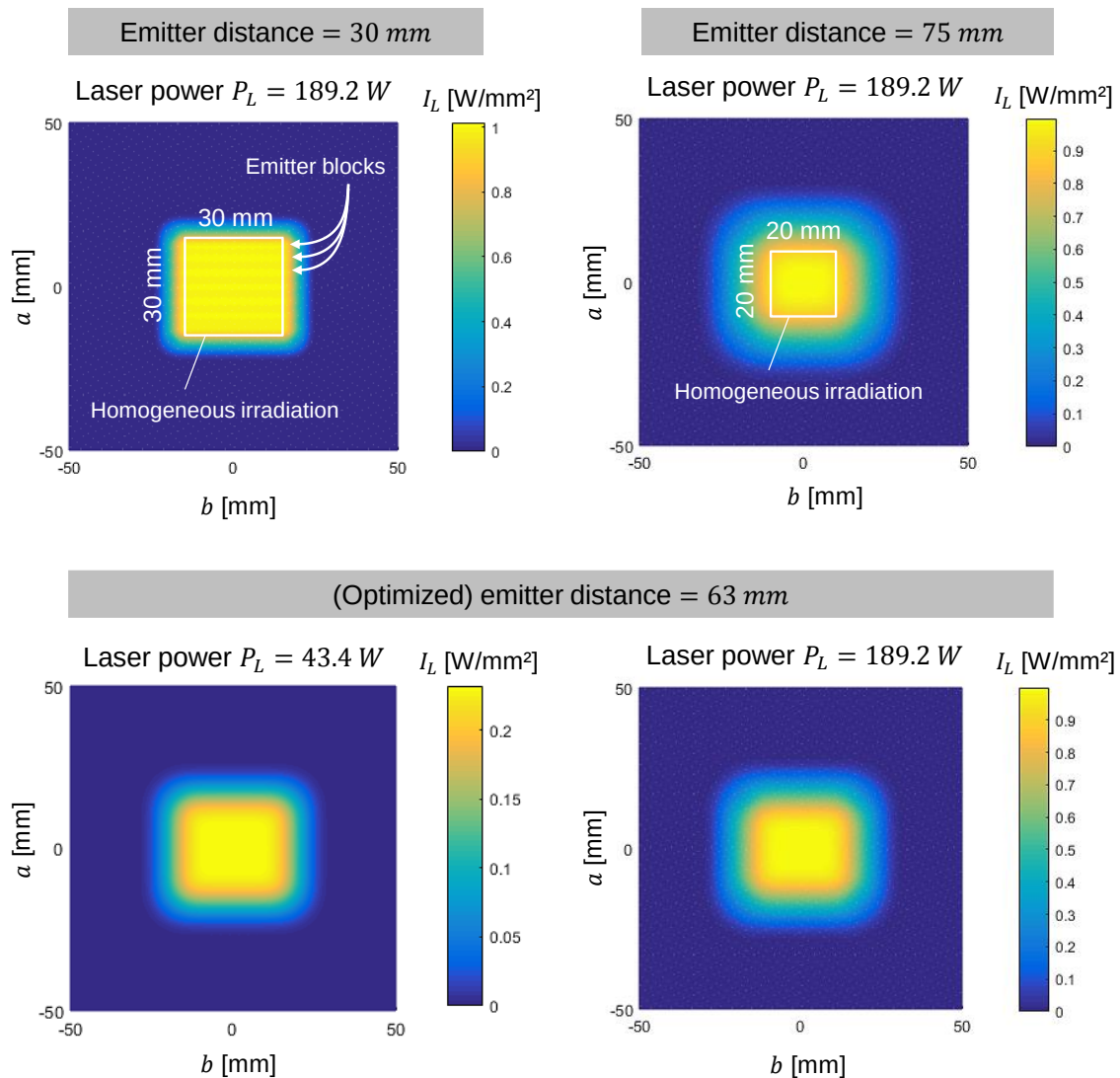


Figure 16.1: Results of the optical simulation on the irradiation homogeneity. Top left: 30 mm distance from the tape surface and 75 mm distance (top right). Bottom: 63 mm distance as a good compromise between homogeneity and high intensity for 43.3 W/emitter (bottom-left) and 189.2 W/emitter (bottom-right)

Ergebnisse der optischen Simulation zur Homogenität der Bestrahlung: Oben links: 30 mm Abstand zur Tapeoberfläche und 75 Abstand (oben rechts). Unten: 63 mm Abstand als guter Kompromiss zwischen homogener Bestrahlung und hoher Intensität für 43,3 W/Emitter (unten links) und 189,2 W/Emitter (unten rechts)

16.2 Pre-Study on the Influence of Conduction in Fiber Direction

Vorstudie zum Einfluss der Wärmeleitung in Faserrichtung

Definition of model deviation

$$\Delta_{\%} = 100 \cdot \left(\frac{T_{n,cond} - 20\text{ }^{\circ}\text{C}}{T_{w,cond} - 20\text{ }^{\circ}\text{C}} - 1 \right) [\%] \quad (16.1)$$

$T_{n,cond}$ Temperature without conduction in fiber direction

$T_{w,cond}$ Temperature with conduction in fiber direction

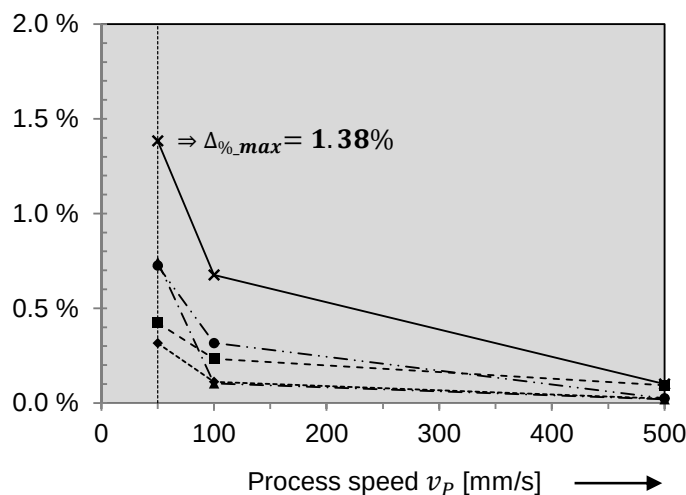
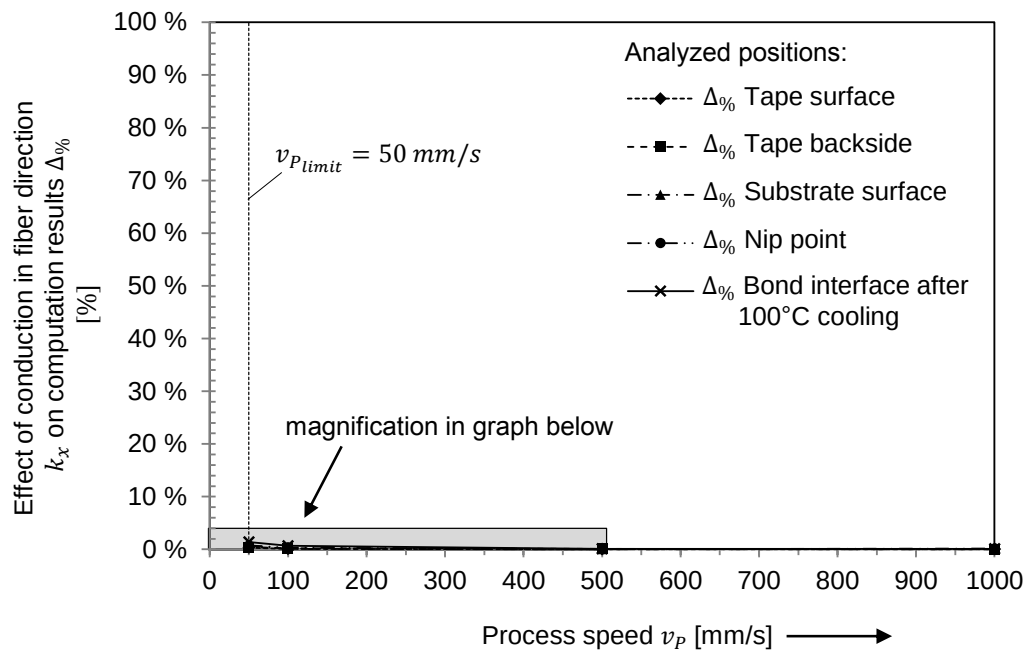


Figure 16.2: Influence of thermal conductivity in fiber direction on the through-thickness temperature distribution for various process speeds (based on material and process parameters of Subsection 5.1.1)

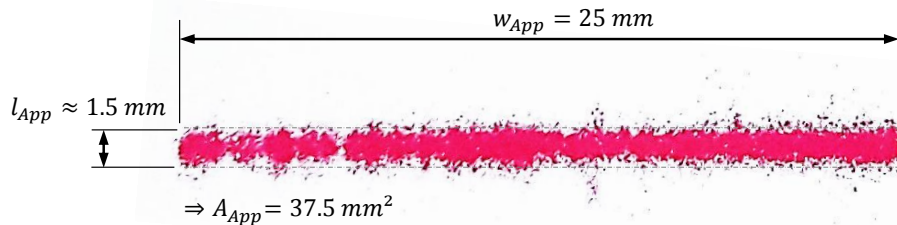
Einfluss der Wärmeleitfähigkeit in Faserrichtung auf die Temperaturverteilung in Dickenrichtung für verschiedene Prozessgeschwindigkeiten (basierend auf Material- und Prozessparametern aus Kapitel 5.1.1.)

16.3 Preliminary Investigations for the Pull-Through Experiment

Voruntersuchung zum Durchzugversuch

16.3.1 Pressure Distribution of the Consolidation Roller on the Tape

Druckverteilung der Konsolidierungsrollen auf einem Tape



Roller diameter $d_R = 20 \text{ mm}$

Cylinder force $F_{cylinder} = 120 \text{ N}$

$\Rightarrow$ Consolidation pressure $P_{App} = 3.2 \text{ N/mm}^2 (32 \text{ bar})$

Figure 16.3: Determination of the consolidation pressure by use of pressure-sensitive paper
Ermittlung des Konsolidierungsdrucks mittels druckempfindlichem Papier

16.3.2 Predetermination of the Actual Nip Point Temperature

Vorermittlung der tatsächlichen Kontaktpunkt-Temperatur

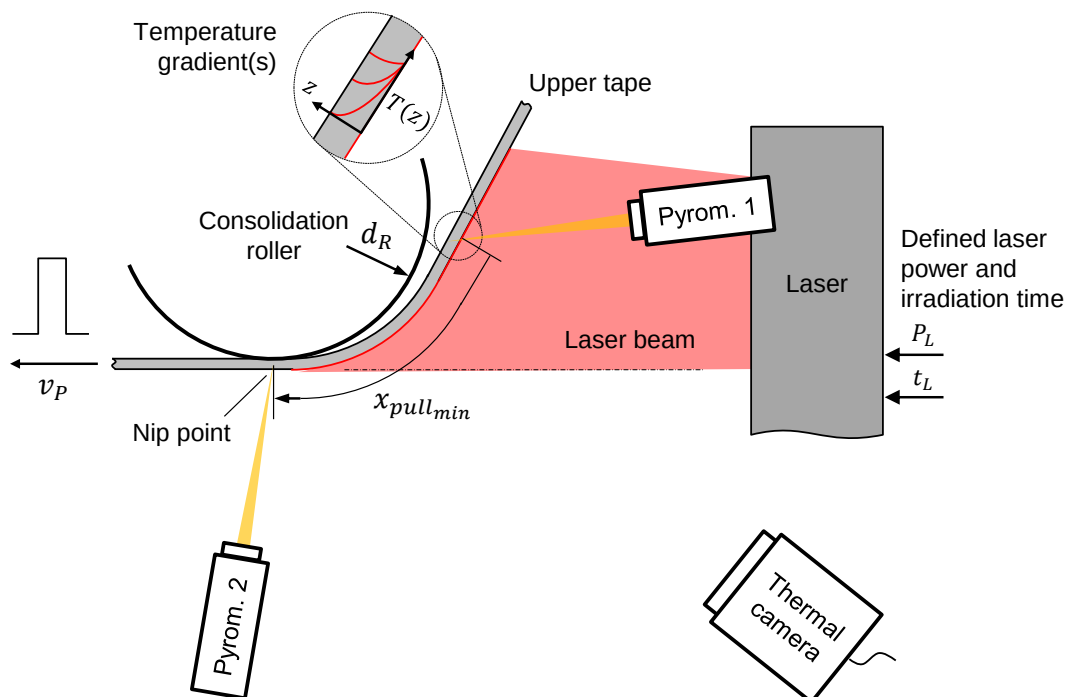


Figure 16.4: Experimental setup of the validation of the actual nip point temperature
Versuchsaufbau zur Validierung der tatsächlichen Kontaktpunkt-Temperatur

17 Appendix V: Equipment Used

Anhang V: Verwendete Gerätetechnik

17.1 Laser Technology

Lasertechnik

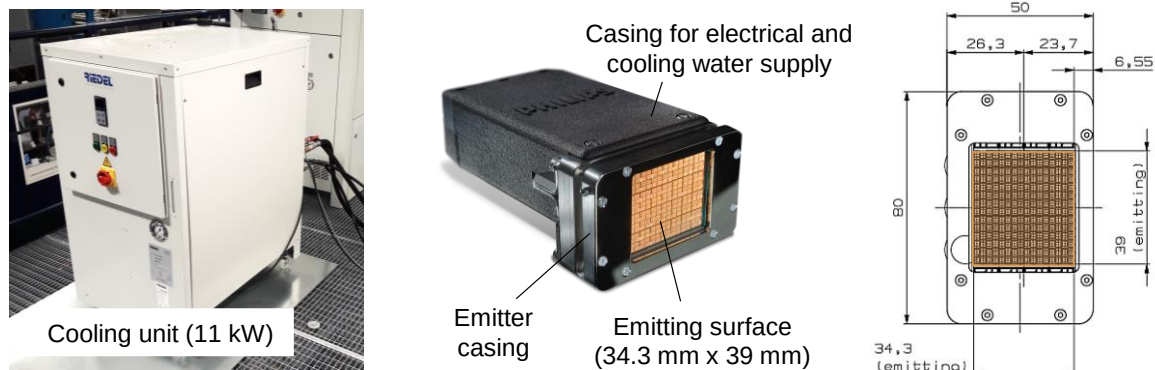


Figure 17.1: VCSEL module that was available during the course of this thesis: Compact module (1600 W overall power)

VCSEL-Modul welches für diese Arbeit zur Verfügung stand: Kompaktes Modul mit 1600 W Gesamtleistung

17.2 Holder for Laser Positioning

Halterung zur Laserpositionierung

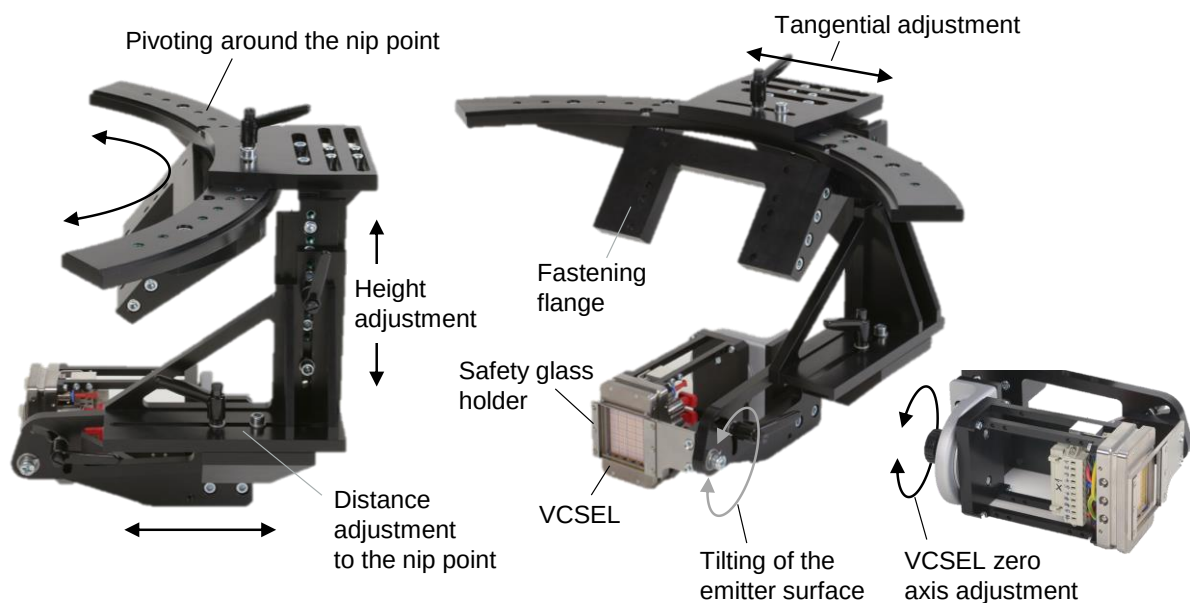


Figure 17.2: Developed laser holder with 6 degrees of freedom

Entwickelte Laserhalterung mit 6 Freiheitsgraden

17.3 Temperature Sensors

Temperatursensoren



Figure 17.3: Temperature sensors used in this thesis. Left: Pyrometer. Right: Thermal imaging camera

Verwendete Temperatursensoren: Links: Pyrometer; rechts: Thermokamera

Table 17.1: Attributes of the pyrometer

Eigenschaften des Pyrometers

Attribute	Description
Manufacturer	LumaSense GmbH
Type	IPE 140/34 MB 5.5
Spectral range	3.43 μm
Temperature range	75-500°C
Min. sample rate	1.5 ms
Measurement uncertainty	< 400°C: 2°C > 400°C: 1°C
Dimensions	195 x 56 x 62.5 mm ³
Weight	550 g

Table 17.2: Attributes of the thermal imaging camera

Eigenschaften der Thermokamera

Attribute	Description
Manufacturer	DIAS Infrared GmbH
Type	Pyroview 380L compact +
Spectral range	8-14 μm
Temperature range	0-500°C
Min. sample rate	14.3 ms (70 Hz)
Measurement uncertainty	2%
Dimensions	65 x 160 x 79 mm ³
Weight	1600 g

18 Appendix VI: Material Properties

Anhang VI: Materialeigenschaften

18.1 PEEK/CF

PEEK/CF

Table 18.1: Averaged material properties of PEEK/CF
Gemittelte Materialeigenschaften von PEEK/CF

Description	Symbol	Value	Unit	Reference
Average conductivity in z	$\bar{k}_z$	0.66	W/(m·K)	[COGS92, p.241]
Average density	$\bar{\rho}$	1570	kg/m ³	[COGS92, p.241]
Average specific heat capacity	$\bar{c}_p$	1320	J/(kg·K)	[COGS92, p.241]
Average thermal diffusivity	$\bar{\alpha}$	0.32	mm ² /s	(Equation 4.10)

Table 18.2: Temperature values of PEEK/CF
Temperaturwerte von PEEK/CF

Description	Symbol	Value	Unit	Reference
Melting temperature	$T_{melting}$	343	°C	[TENC17, p. 1]
Recommended processing temperature	T_P	370-400	°C	[TENC17, p. 2]
Degradation temperature (for t < 15 s; p. 199)	$T_{degradation}$	550	°C	[COGS92, p.109]
Degradation temperature (for t < 2 s)	"	600	°C	[COGS92, p.109]

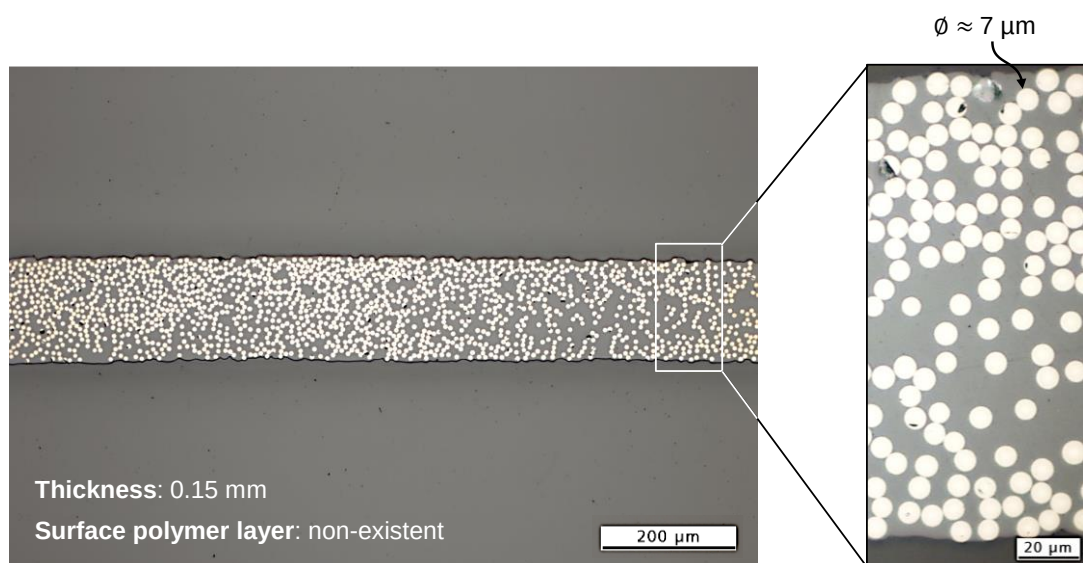


Figure 18.1: Microsection of the used PEEK/CF tape
Querschliffbild des verwendeten PEEK/CF-Tape

18.2 HDPE/GF

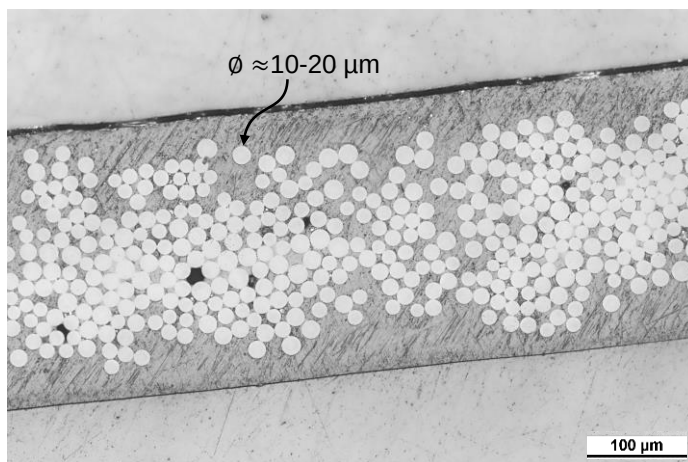
HDPE/GF

Table 18.3: Averaged material properties of HDPE/GF
Gemittelte Materialeigenschaften von HDPE/GF

Description	Symbol	Value	Unit	Reference
Average conductivity in z	$\bar{k}_z$	0.72	W/(m·K)	[CELA17]
Average density	$\bar{\rho}$	1710	kg/m ³	[CELA17]
Average specific heat capacity	$\bar{c}_p$	1180	J/(kg·K)	[CELA17]
Average thermal diffusivity	$\bar{\alpha}$	0.36	mm ² /s	(Equation 4.10)

Table 18.4: Temperature values of HDPE/GF
Temperaturwerte von HDPE/GF

Description	Symbol	Value	Unit	Reference
Melting temperature	$T_{melting}$	127	°C	[CELA17]
Recommended processing temperature	T_P	175-230	°C	[SABI17]
Minimum degradation temperature	$T_{degradation}$	233	°C	[BEYL02, p. 124]
1% thermal decomposition	"	275	°C	[BEYL02, p. 124]

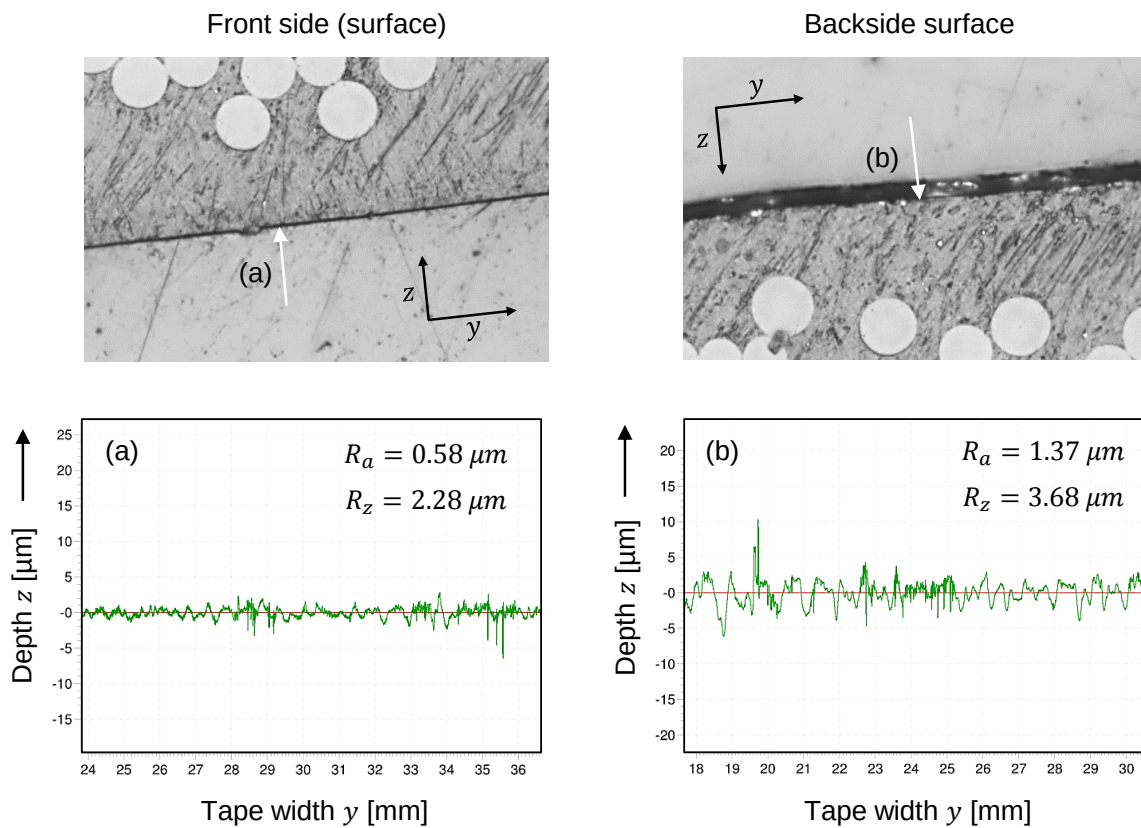


Thickness d_{tape} : 0.25 mm
Fiber content by weight: 70% by wt.
Fiber content by volume: 47% by vol.
Surface polymer layer: $\approx 25 \mu\text{m}$

Figure 18.2: Microsection of the used HDPE/GF tape
Querschliffbild des verwendeten HDPE/GF-Tapes

18.3 Surface Roughness of the HDPE/GF Tapes

Oberflächenrauheit der HDPE/GF-Tapes



R_a : average peak-to-valley height R_z : average surface roughness

Figure 18.3: Tactile measurements of the original surface roughness of the HDPE/GF tapes.
Left-hand side: front side, right-hand side: backside

Taktile Messungen der ursprünglichen Oberflächenrauheit der HDPE/GF-Tapes. Links: Vorderseite, rechts: Rückseite

19 Appendix VII: Extended Thermal Material Properties

Anhang VII: Erweiterte thermische Materialeigenschaften

19.1 Specific Heat Capacity, Enthalpy of Fusion and Crystallization

Spezifische Wärmekapazität, Schmelz- und Kristallisationsenthalpie

Before investigations showed that the specific heat capacity c_p can be averaged for practical-purpose accuracies (Section 5.5), it was unclear whether its dependency on temperature was a significant effect to be modelled for accurate results.

In this context, it was also unknown whether *enthalpy of fusion* and *crystallization* do effect the temperature development. Therefore, the detailed numerical model (Subsection 5.1.2) included temperature-dependent specific heat capacity $c_p(T)$, enthalpy of fusion and crystallization. Subsequently, the modelling is explained:

During the heating and cooling of polymers, a heat sink and heat source emerges, due to the enthalpy of fusion and crystallization. In general, there are two ways to consider these phenomena in simulations [DYJA16]:

- Method 1: Directly by additional heat source / heat sink terms
- Method 2: Indirectly via the temperature-dependent specific heat capacity

Implementing additional heat source / heat sink terms (Method 1) was found to create high practical efforts and the computation time of the non-linear system was high. Method 2: The enthalpy of fusion can be noticed as a positive peak within the heat capacity curves. This effect can be utilized for modelling. VOR DEM ESCHE used an exponential term to describe the enthalpy of fusion for PEEK [ESCH01, p. 67-68]. Analogously, the enthalpy of crystallization can be noticed as a negative peak.

$$c_p(T) = -\Delta c_{p,cryst.} \cdot \exp \left[-\frac{2}{\Delta T_{cryst.}} (T_{cryst.} - T)^2 \right] + \Delta c_{p,melting} \cdot \exp \left[-\frac{2}{\Delta T_{melting}} (T_{melting} - T)^2 \right] - 3 \cdot 10^{-3} \cdot T^2 + 3.5 \cdot T + 737 \quad (19.1)$$

$\Delta c_{p,melting}$ fusion peak	1286 J/(kg·K) [ESCH01, S. 68]
$\Delta c_{p,cryst.}$ crystallization peak	230 J/(kg·K) derived from [GAO00a, p. 521]
$\Delta T_{melting}$ width of fusion heat peak	45°C [ESCH01, S. 68]
$\Delta T_{cryst.}$ width of crystallization peak	45°C
$T_{melting}$ melting temperature	343°C
$T_{cryst.}$ crystallization temperature	183°C derived from [GAO00a, p. 521]

with T in °C.

Data for the latent heat of fusion and crystallization of PEEK/CF were determined experimentally by GAO & KIM:

$$L_{m,i} = \frac{\Delta c_p}{\Delta T_i} \quad (19.2)$$

$L_{m,melting}$ latent heat fusion	36250 J/kg [GAO00a, p. 521]
$L_{m,cryst.}$ latent heat crystallization	10333 J/kg [GAO00a, p. 521]

It has to be mentioned that the magnitude of the fusion enthalpy and crystallization peaks does also depend to some degree on the heating/cooling rate [KOEL08, p. 49]. This effect was neglected.

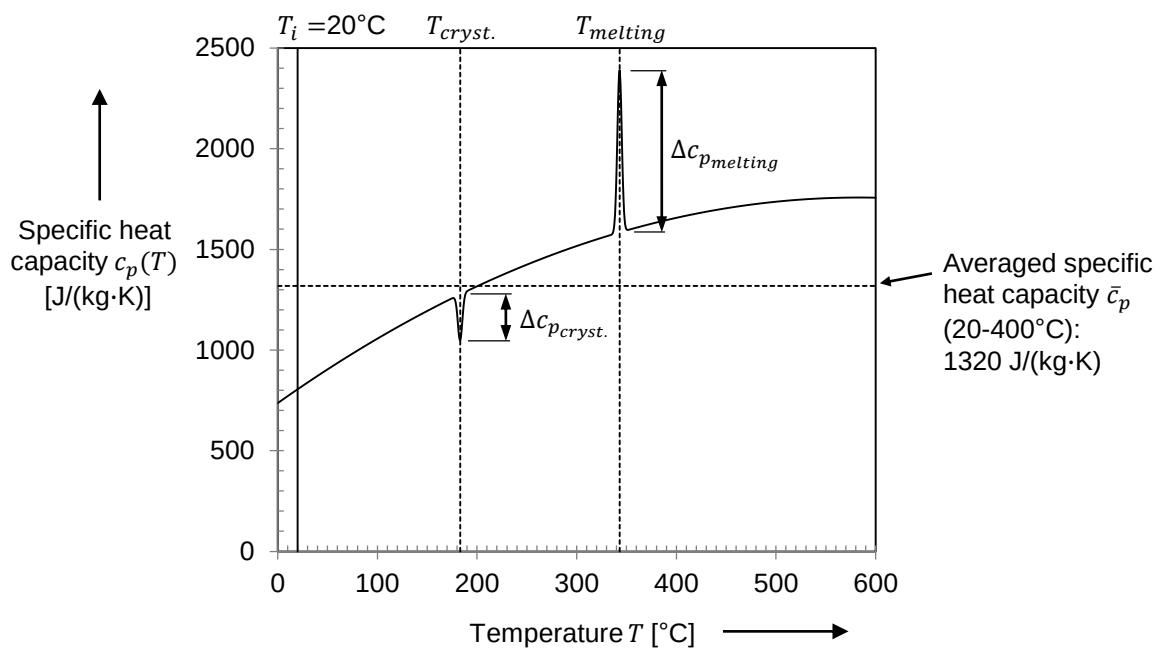


Figure 19.1: Temperature-dependent specific heat capacity for PEEK/CF with enthalpy of fusion and crystallization

Temperaturabhängige spezifische Wärmekapazität von PEEK/CF mit Schmelz- und Kristallisationsenthalpie

During model analysis, it was found that the choice of the initial temperature window ($T_i \rightarrow T_{max}$) averaging $c_p(T)$ did influence the modelling accuracy. This problem however was solved by iterative optimization of the temperature window (notice that the final surface temperature is not known before the first computation).

19.2 Temperature-Dependent Flexural Modulus

Temperaturabhängiger Biegemodul

Database and Assumptions Made

The transversal tensile modulus at room temperature of PEEK/CF tape $E_{t_{tape}}$ (60 vol% fiber content) is taken from [TENC17, p. 1]: 10.000 N/mm²

The *flexural* modulus $E_{f_{tape}}$ is assumed $\approx$ equal to the *tensile* modulus $E_{t_{tape}}$, as in [VICT17, p. 1] [TENC17, p. 1]

Temperature-dependent flexural modulus of neat PEEK $E_{f_{PEEK}}(T)$ is modelled according to data taken from [SOLV16, p. 24]:

$$E_{f_{PEEK}}(T) = 3 \cdot 10^{-6} \cdot T^4 - 0.0015 \cdot T^3 + 0.1267 \cdot T^2 - 3.4114 \cdot T + 3734.5 \quad (19.3)$$

Flexural modulus > 200°C is assumed negligible compared to the solid state of the tape ($\approx$ factor 30).

The temperature-dependent *flexural* modulus of the tape $E_{f_{tape}}(T)$ is derived from the *rule of mixture* assumption:

$$E_{f_{tape}}(T) = \frac{E_{f_{PEEK}}(T) \cdot E_{f_{CF}}}{E_{f_{PEEK}}(T) \cdot V_{M_{CF}} + E_{f_{CF}} \cdot V_{M_{PEEK}}} \quad (19.4)$$

($V_{M_{CF}}$ is the volume fraction of the carbon fiber and $V_{M_{PEEK}}$ that of the PEEK.)

The temperature-dependent flexural modulus of the PEEK/CF tape yields:

$$E_{f_{Tape}}(T) = 7 \cdot 10^{-6} \cdot T^4 - 0.0041 \cdot T^3 + 0.3424 \cdot T^2 - 9.2201 \cdot T + 10093 \quad (19.5)$$

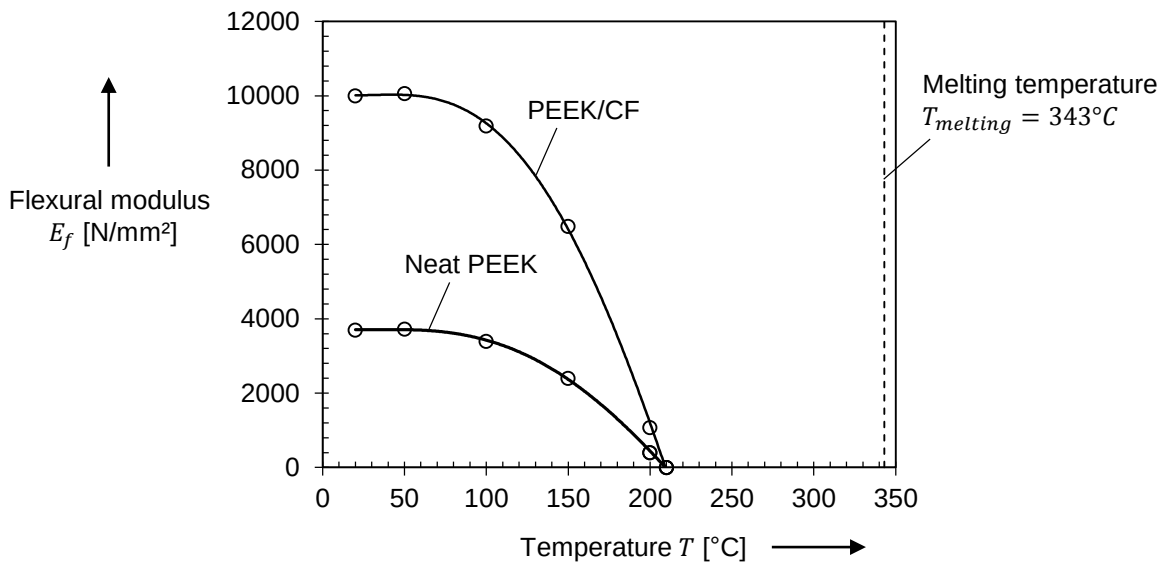


Figure 19.2: Modelled temperature-dependent flexural modulus of PEEK, based on [SOLV16, p. 24] [TENC17, p. 1]

Modellierter temperaturabhängiger Biegemodul von PEEK

19.3 Temperature-Dependent Thermal Conductivity

Temperaturabhängige Wärmeleitfähigkeit

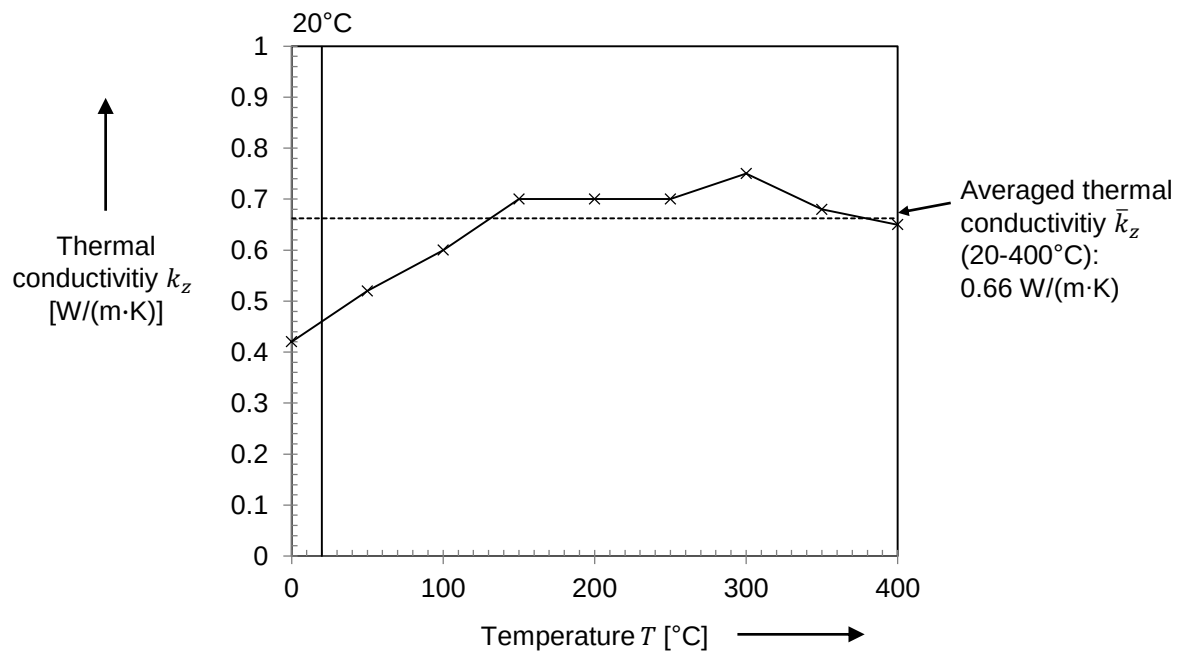


Figure 19.3: Temperature-dependent thermal conductivity of PEEK/CF [COGS92, p. 241]

Temperaturabhängige Wärmeleitfähigkeit von PEEK/CF

19.4 Averaged Radiative Heat Transfer Coefficient

Gemittelter konvektiver Wärmeübergangskoeffizient

$$\dot{Q}_{rad} \approx \sigma \cdot A \cdot (\varepsilon T^4 - \varepsilon_0 T_0^4) \quad (19.6)$$

$\dot{Q}_{rad}$ radiative heat flow

σ Stefan-Boltzmann constant $5.67 \cdot 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$

ε emission coefficient surface 1 (maximum)

ε_0 emission coefficient environment 0 (environmental reflection infinitely low)

T temperature of the body 600°C (maximum)

T_0 ambient temperature 20°C

A emitting surface 1 mm^2 (universal unit)

Linearization leads to:

$$\dot{Q}_{rad} \approx 4\sigma A T^3 (T - T_0); \quad \Rightarrow h_{rad} = 4\sigma A T^3 \quad [\text{WETZ07}] \quad (19.7)$$

Averaging from 20°C to 600°C yields: $\bar{h}_{rad} = 57 \text{ W}/(\text{m}^2 \cdot \text{K})$

19.5 Line-Speed-Dependent Convective Heat Transfer Coefficient at Various Heating Lengths

Bewegungsgeschwindigkeitsabhängiger konvektiver Wärmeübergangskoeffizient bei verschiedenen Erwärmungsstrecken

In Section 4.3, the convective heat flow $\dot{Q}_{conv}$ was found to be negligible, due to the significantly higher thermal resistance R_{conv} compared to the internal heat flow resistance of conduction R_{cond} . Whether this still holds true for higher heating lengths/speeds depends on the heat transfer coefficient $h_{conv}(v_p, x_L)$.

Therefore, the change of h_{conv} was determined for various process speeds and heating/characteristic lengths, on basis of an *idealized flat plate* with equations for the fluid dynamics of the ambient air at the boundary layer based on [BERG11, p. 401] [BAEH13, p. 354] and [ÇENG15, p. 431] and data taken from [LI15, p. 561-562]. Figure 19.4 shows the result for two heating lengths (50 mm and 500 mm) in combination with the respective irradiation time t_L .

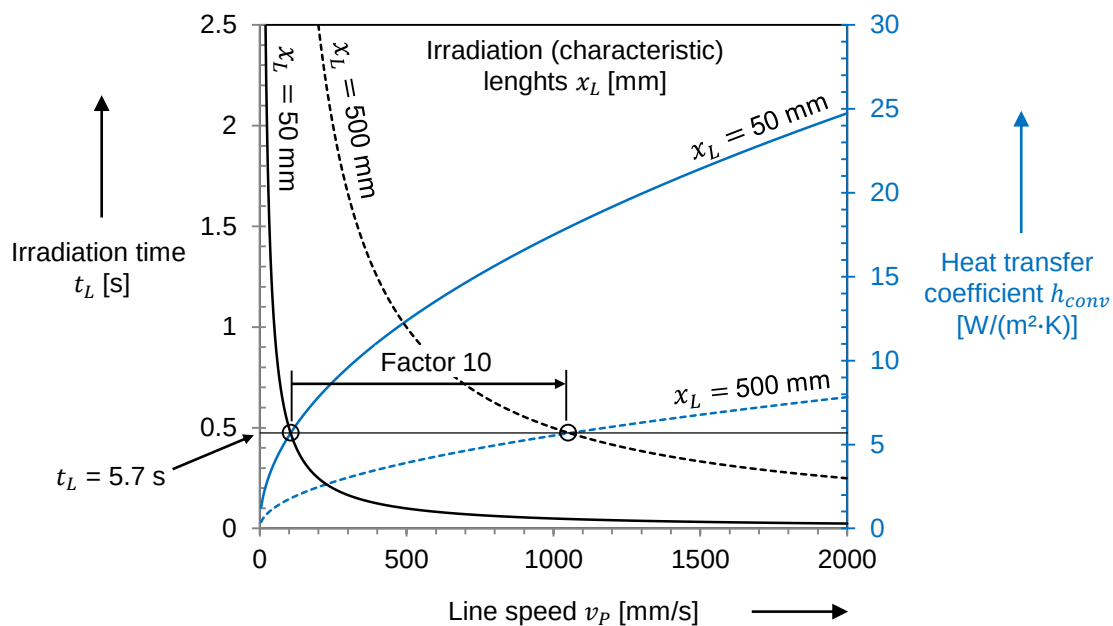


Figure 19.4: Heat transfer coefficient to air and irradiation time as a function of line speed and irradiation/characteristic length

Wärmeübergangskoeffizient an Luft und Bestrahlungszeit als Funktion der Bewegungsgeschwindigkeit und Bestrahlungsstrecke/ charakteristische Länge

The graphs shows that at higher process speeds v_p and irradiation lengths x_L , the heat transfer coefficient h_{conv} remains equal. The reason for this is that two effects cancel each other out: h_{conv} increases by higher speed but simultaneous decreases, due to changing flow conditions at the boundary layer. Therefore, the thermal resistance R_{conv} remains constant. Because the irradiation time t_L remains also equal, the heat losses by convection $\dot{Q}_{conv}$ stay the same. The simplification made in Section 4.3 does therefore apply for all process speeds.

20 Appendix VIII: Material Properties reg. Bonding

Anhang VIII: Materialeigenschaften bzgl. des Fügens

20.1 Reptation/Welding Time as Function of Temperature for PEEK

Reptations-/Fügeschweißzeit als Funktion der Temperatur für PEEK

Model by KHAN et al.

$$t_w(T) = 2 \cdot 10^{-5} \cdot \exp(43000/RT) \quad (20.1)$$

R universal gas constant	8.31451 J/(K·mol)
T temperature	K
$t_w(T)$ temperature-dependent reptation/welding time	ms

Model of SONMEZ & HAHN

$$t_w(T) = t_r \cdot \exp \left[\frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right] \quad (20.2)$$

R universal gas constant	(see above)
T temperature	K
t_r constant	0.11 s
E_a activation energy	67300 J/mol
T_{ref} reference temperature	673°K

20.2 Intimate Surface Contact Development as a Function of Pressure and Surface Roughness

Ausbildung des intimen Flächenkontaktes als Funktion von Druck und Oberflächenrauheit

Model by MANTEL & SPRINGER under Isothermal and Isobaric Conditions

$$D_{IC}(t) = R^* \left[\frac{P_{App} \cdot t_{App}}{\mu_0(T)} \right]^{1/5} \quad (20.3)$$

R^* "lumped" geometrical constant for surface roughness	0.29 for typical PEEK/CF [MANT92b, p. 2385]
P_{App} consolidation pressure	3.29 N/mm ² (32.9 bar)
$\mu_0(T)$ temperature-dependent zero-shear rate viscosity	<u>Varies significantly</u> among models (and types of PEEK) in the literature; next page

20.3 Temperature-Dependent Viscosity of PEEK/CF and PEEK

Temperaturabhängige Viskosität von PEEK/CF und PEEK

Viscosity Models (Semi-Empirical Arrhenius Relation)

$$\mu_0(T) = A \cdot \exp(B/T) \quad (20.4)$$

T Temperature	K	
PEEK/CF mixture		
A	B	[Source]
643 Ns/m ²	4367 K	[KHAN10a, p. 101]
132.95 Ns/m ²	2969 K	[MANT92a, p. 2374]
1.14×10^{-12} Ns/m ²	26300 K	[LEE87a, p. 1053]
0.0037 Ns/m ²	11115 K	[KHAN12, p. 487]
Neat PEEK		
A	B	[Source]
1.13×10^{-10} Ns/m ²	19100 K	[MANT92a, p. 2374]
0.2037 Ns/m ²	4871 K	[KHAN12, p. 487]

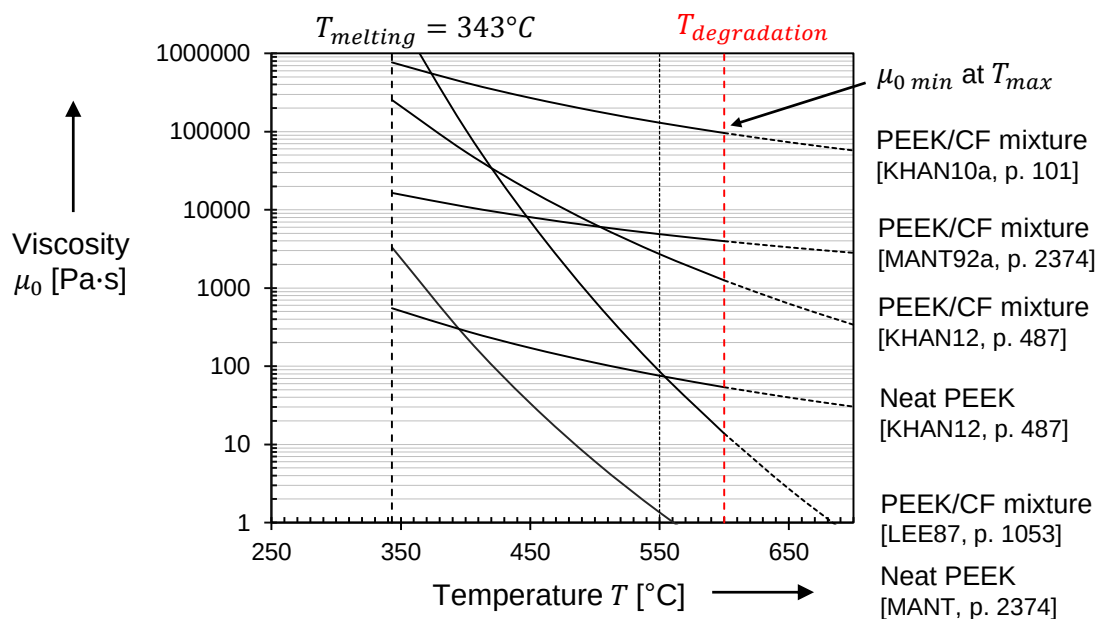


Figure 20.1: Temperature-dependent viscosity of PEEK/CF mixture and neat PEEK according to various models from the literature. The models vary in several decimal powers.

Temperaturabhängige Viskosität einer PEEK/CF-Mischung und reinem PEEK nach verschiedenen Modellen aus der Literatur. Die Modelle variieren in einigen Zehnerpotenzen.

20.4 Degradation Temperature of PEEK

Degradationstemperatur von PEEK

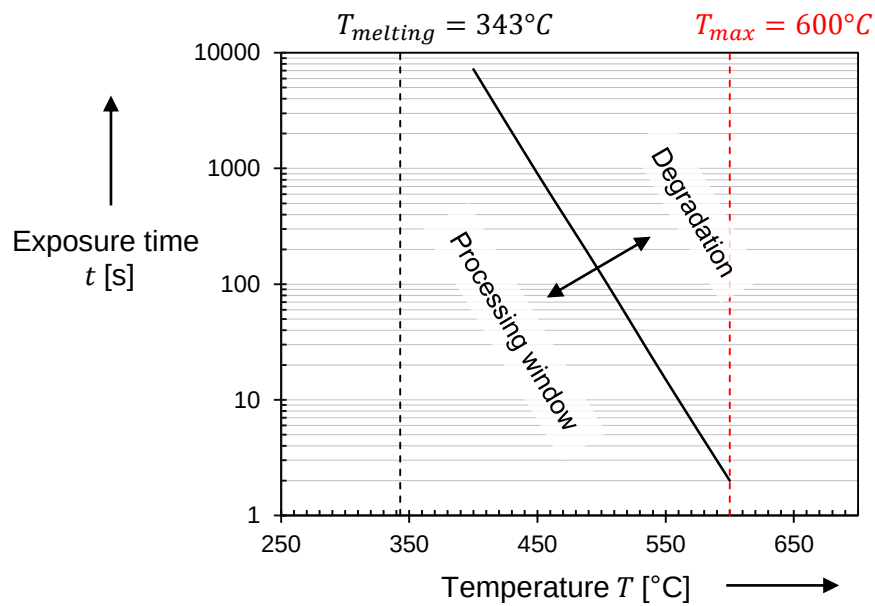


Figure 20.2: Degradation of PEEK as a function of temperature and exposure time, based data from [COGS92, p. 101]; form of expression adapted from [LATR03, p. 34]

Degradation von PEEK als Funktion der Temperatur und deren Wirkzeit

21 Appendix IX: Visualizations

Anhang IX: Visualisierungen

21.1 Geometrical Sizes in Heating of Tapes by Means of Laser

Größenordnungen bei der Erwärmung von Tapes mittels Laser

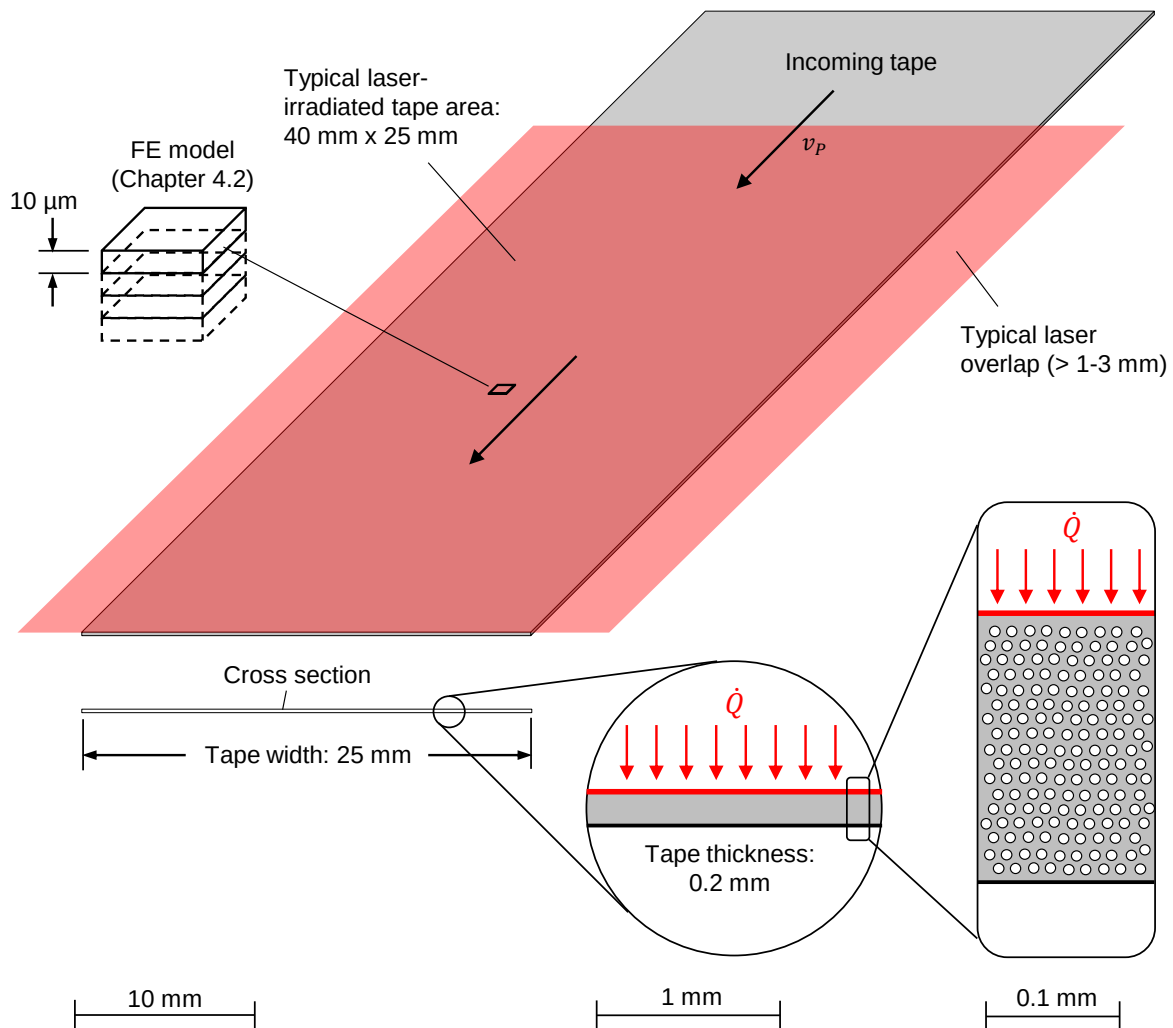


Figure 21.1: True-to-scale drawing of the incoming tape with typical geometries and laser irradiation length/width. A single tape element is depicted, which undergoes a relative long irradiation length compared to its thickness. Consideration of the relative scales alone indicates that the heat transfer problem is dominated by the through-thickness direction ($\rightarrow$ 1-dimensional heat transfer problem).

Maßstabsgerechte Zeichnung des einlaufenden Tapes mit typischen Tapeabmaßen und typischer Laserbestrahlungslänge und -breite. Ein einzelnes Tape-element ist dargestellt. Betrachtung der relativen Skalen alleine lässt darauf schließen, dass das Wärmeleitungsproblem durch die Materialdickenrichtung dominiert wird ($\rightarrow$ 1-dimensionales Wärmeleitungsproblem).

21.2 Geometry and Material Conditions near the Tape Surface

Geometrie- und Materialbedingungen nahe der Tapeoberfläche

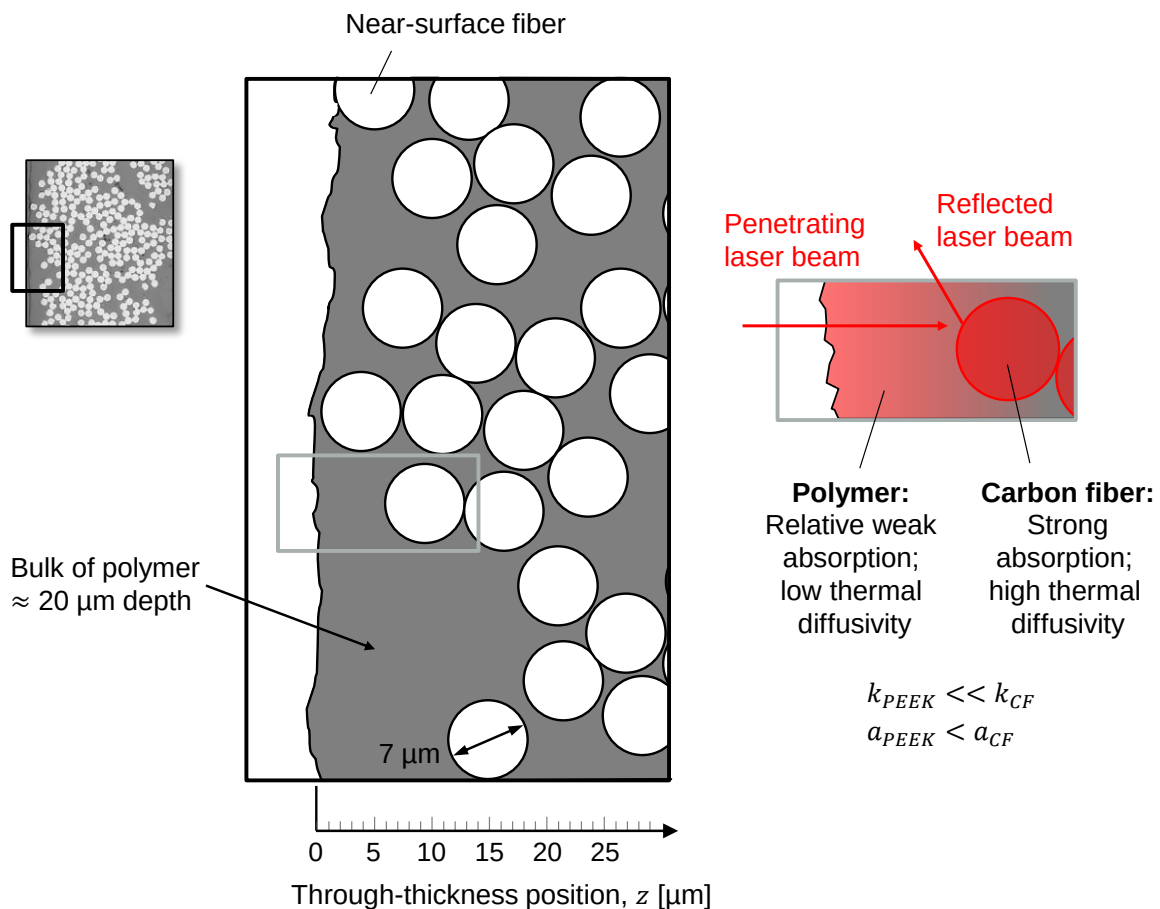


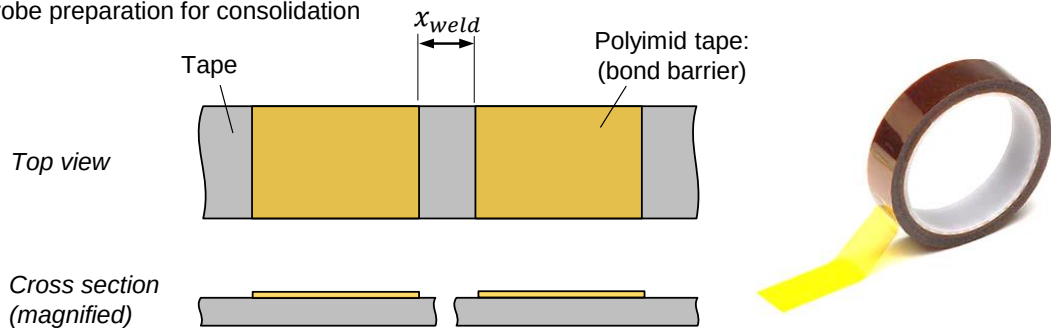
Figure 21.2: Geometrical conditions near a typical tape surface. It can be observed that the assumption of homogeneous thermal material properties holds not true anymore for very short irradiation times (< 10 ms), as in those conditions the thermal problem is dominated by the micro heat flow. The laser penetration depth should in this case be considered as well.

Geometrische Bedingungen nahe der Tapeoberfläche. Man kann erkennen das die Annahme homogener thermischer Werkstoffeigenschaften nicht mehr gilt bei sehr kurzen Bestrahlungszeiten (< 10 ms), weil bei diesen Zuständen der Wärmefluss auf der Mikroskala das thermische Problem bestimmt. Die Laserstrahleindringtiefe sollte in diesem Fall ebenfalls betrachtet werden.

21.3 Probe Preparations

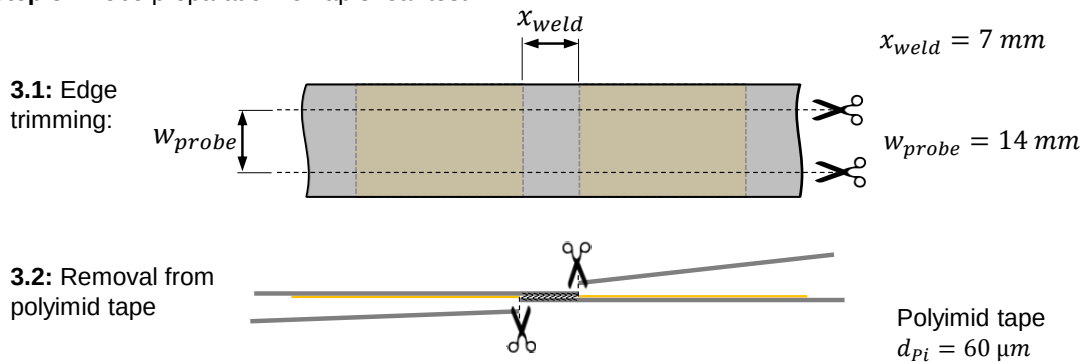
Probenvorbereitungen

Step 1: Probe preparation for consolidation



Step 2: Consolidation of the probe, together with an unprepared tape (see Chapter 6.2.1)

Step 3: Probe preparation for lap shear test



Step 4: Lap shear testing

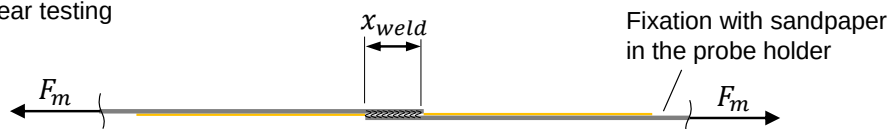


Figure 21.3: Probe preparation steps

Schritte bei der Probenpräparation

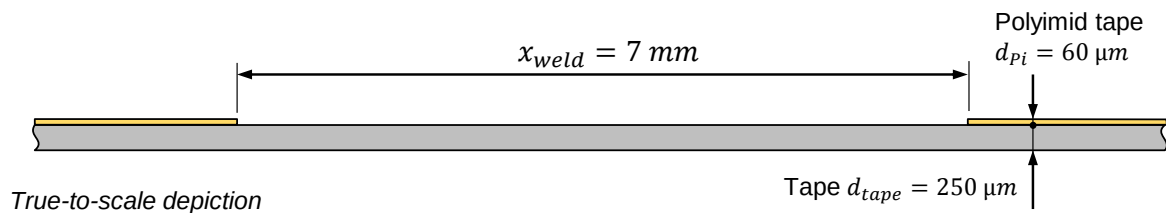


Figure 21.4: True-to-scale depiction of the probe with the 250 μm-thick tape and the 60 μm-thick Polyimide tape

Maßstabsgerechte Darstellung der Probe mit dem 250 μm dicken Tape und dem 60 μm dicken Polyimide-Klebeband

