

ARTICLE

Influence of the spray angle on thermally sprayed heating coatings

Einfluss des Spritzwinkels auf thermische Spritz-Heizschichten

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Abstract

Temperature control of mould surfaces is of high relevance for part quality in moulding processes. Due to highly dynamic heating behaviour, heating elements applied by thermal spraying can be an alternative to existing tempering methods. To ensure the feasibility of these heating coatings on industry-relevant moulds, the coating system needs to be applied onto more demanding non-flat geometries. For this purpose, the spray angle of the plasma spraying process is varied during the application of the titanium oxide/chromium oxide heating coating and the insulating aluminium oxide coating. Subsequently, the results are related to application-oriented cavity shapes. Spray angle deviations from the optimal perpendicular angle are leading to decreasing dielectric strength of the coating system and an increase of the electrical resistivity. Additionally, the application efficiency reduces with the spray angle variation. Knowledge of the spray angle's influence on coating properties can help to coat more demanding shapes, including free formed surfaces or corners.

KEYWORDS

ceramic coatings, heating element, injection moulding, temperature control, thermal spraying

Abstract

Die Temperierung von Werkzeuoberflächen ist in Formgebungsprozessen von hoher Relevanz für die Bauteilqualität. Aufgrund ihres hochdynamischen Erwärmungsverhaltens können Heizelemente, die durch thermisches Spritzen appliziert werden, eine Alternative zu bestehenden Temperierungsverfahren darstellen. Um die Anwendbarkeit dieser Heizschichten auf industrierelevanten Spritzgießwerkzeugen zu gewährleisten, muss das Schichtsystem auf anspruchsvollere, nicht flache Geometrien aufgebracht werden. Zu diesem

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Zweck wird der Spritzwinkel des Plasmaspritzprozesses während der Applikation der Titanoxid/Chromoxid-Heizschicht und der isolierenden Aluminiumoxid-Beschichtung variiert. Anschließend werden die Ergebnisse in Bezug zu anwendungsorientierten Kavitäten gesetzt. Spritzwinkelabweichungen vom optimalen senkrechten Winkel führen zu einer Abnahme der Durchschlagsfestigkeit des Schichtsystems und zu einem Anstieg des elektrischen Widerstandes. Außerdem sinkt der Auftragswirkungsgrad mit der Variation des Spritzwinkels. Die Kenntnis des Einflusses des Spritzwinkels auf die Beschichtungseigenschaften kann helfen, anspruchsvollere Spritzgießwerkzeuge zu beschichten, einschließlich frei geformter Oberflächen oder Kanten.

SCHLÜSSELWÖRTER

Heizschichtelement, Keramische Beschichtung, Spritzgießen, Temperaturkontrolle, Thermisches Spritzen

1 | INTRODUCTION

In the field of plastic production, injection moulding is one of the most attributed manufacturing processes [1]. In this process, the temperature distribution of the mould plays a significant role of the quality of the produced parts. Shrinkage and warpage of injection moulded components are greatly influenced by the thermal properties of the polymer [2]. Controlled local cavity temperature can reduce warpage in the moulded parts and enables the production of thin-walled components. Existing temperature control solutions are currently not highly dynamic and have limited applicability [3]. A thermally sprayed heating coating system can influence the temperature in these processes as the heat is generated directly at the contact area to the polymer melt [4]. Due to its dynamic and variothermal heating behaviour, a thermally sprayed heating coating is an attractive alternative to existing tempering systems.

Thermally sprayed heating coatings utilize the effect of Joule heating in conductive and semiconductive materials to generate the required heat. Metallic heating coatings such as nickel chromium are applied in meandering paths on the substrate to generate sufficient heating power [5, 6]. Semiconductors can be applied over a larger area and with a greater coating thickness due to their higher electrical resistivity [7]. The used heating coating system in this study is a semiconductive ceramic titanium oxide/chromium oxide material, which has been investigated in previous studies [8]. Several studies can be found on the semiconducting properties of titanium suboxides [9, 10]. A thermally sprayed heating coating system is typically composed of a bond coating and

insulation coatings in which a heating coating is embedded, Figure 1.

The heating coating system have been previously applied on flat cavities of an injection tool [11]. Processing trials have shown that an influence on the part quality and a reduction in warpage have been achieved [12]. However, for the application of the thermally sprayed heating coating system in an industrial environment, the usability of the heating coating on demanding geometries must be ensured. Industrial relevant mould cavities have various geometries, and during the application of the heating coating on these non-flat geometries, the optimal vertical spray angle for thermal spraying cannot be maintained.

In studies carried out at the Institute for Plastics Processing (IKV) at the RWTH Aachen, possible application spots for the thermally sprayed heating coatings system were simulated to reduce warpage on demanding non-flat components. It became evident that the use of heating coatings is particularly useful in edge areas of

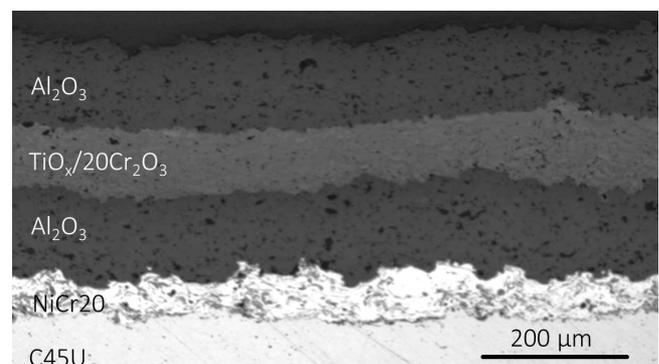


FIGURE 1 Cross section of a ceramic heating coating system.

the cavity where a spray angle perpendicular to the cavity cannot be guaranteed. Therefore, the spraying angle is varied, and the influence on the properties of the heating coating system is investigated in this study. This study contributes to the necessary preliminary investigations to determine how thermally sprayed heating coatings can be transferred to demanding and application-oriented geometries.

The influence of the spray angle on plasma sprayed coatings has already been investigated. The highest coating thickness of hard based material coatings is achieved at a spray angle of $\alpha = 80^\circ\text{--}90^\circ$ [13]. If the spray angle deviates from this, the coating thickness per pass is reduced. Furthermore, the spray angle does have an influence on the distribution of microcracks [14].

2 | METHODS AND MATERIALS

In order to investigate the influence of the spray angle on the properties of thermally sprayed heating coatings, the coating system was applied to the mild steel substrate C45 U with dimensions of $100 \times 50 \times 5 \text{ mm}^3$. This material is typical for the moulds used in plastic injection moulding. To activate and roughen the substrate surface, it was blasted with corundum of the fraction F20 at a pressure of $p = 5 \text{ bar}$. Subsequently, the respective layers of the coating system were applied using atmospheric plasma spraying with the TriplexPro210 gun Oerlikon Metco Europe GmbH, Wohlen, Switzerland. First, a nickel chromium bond coating was applied. Afterwards, an aluminium oxide based insulation was applied. During the coating process, the gun was mounted on a robot that coated the substrates in a meandering motion. The spray angle was kept perpendicular to the substrate for both coatings, in order to separately investigate the influence of spray angle on the properties of the heating coating. Then, the titanium oxide/chromium oxide heating coating was applied with the spray angle varied to the optimal perpendicular spray angle, Table 1.

The angle was varied for both the positive and negative values of the angle deviation, to determine whether a stabbing or dragging motion of the particle-free jet also has an influence on the properties of the heating coating. Additionally, a specimen with angle variation was coated with the gun moving both dragging and stabbing over the specimen as in a possible application case, Figure 2. The parameters used to coat the heating coating system based on previous investigations by the authors.

To determine the thickness of the heating coating system, a micrometer measuring screw was used. By keeping the number of transitions the same for each application, an examination of the deposition efficiency is

TABLE 1 Spray angle variation.

Specimen	Spray angle deviation of perpendicular angle	Movement direction of plasma jet
1	-10°	Dragging
2	$+10^\circ$	Stabbing
3	$-/+10^\circ$	Dragging & stabbing
4	-20°	Dragging
5	$+20^\circ$	Stabbing
6	$-/+20^\circ$	Dragging & stabbing
7	-30°	Dragging
8	$+30^\circ$	Stabbing
9	$-/+30^\circ$	Dragging & stabbing
10	-45°	Dragging
11	$+45^\circ$	Stabbing
12	$-/+45^\circ$	Dragging & stabbing
13 (reference)	0°	Perpendicular

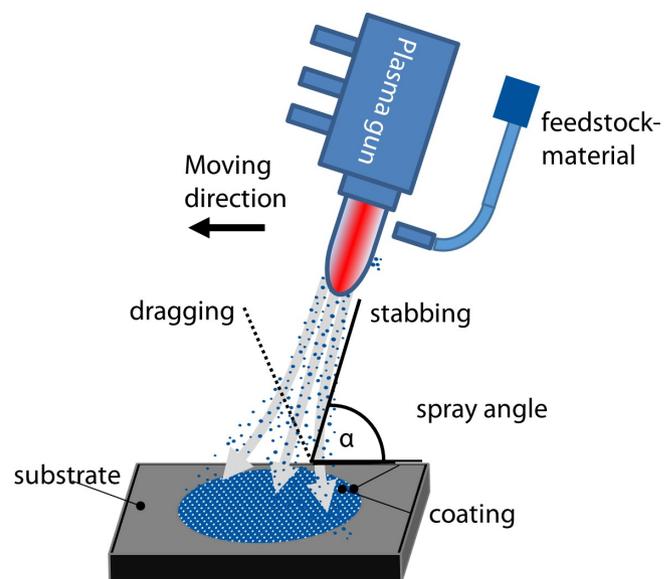


FIGURE 2 Schematic illustration of the spray angle variation.

possible. The electrical resistance of the titanium oxide/chromium oxide heating coating was determined using a four-wire measurement with TM-508 A (Isothermal Technology, Southport, United Kingdom).

The investigation of the heating behaviour of the heating coating and determination of the dielectric strength of the insulation coating were carried out on a test bench specially manufactured for these purposes by RST Rostock System-Technik GmbH, Rostock, Germany.

In the investigation of the heating behaviour of the heating coating, it is supplied with voltage via an electrical power source controlled by a LabView program. The temperature on the specimen surface is monitored using an infrared temperature sensor and used to control the power source. A thermography camera, for which the emission coefficient has been adjusted to an as-sprayed rough reference specimen, records the thermographic image of the specimen surface to observe the temperature distribution on the heating coating. The specimens were connected to the power source by a clamp contact and heated to a temperature of $T = 150^{\circ}\text{C}$ by controlling the applied voltage, as this temperature was sufficient in the previous investigations of the heating coating system in the plastic injection moulding process. Through the examination of the heating coating systems on the heating cycle test bench, it can be investigated whether the variation of the spray angle has an influence on the temperature distribution of the heating coating. This would show whether non-perpendicular applied particles form areas of cracks within the heating coating, which would lead to hotspots during operation. These hotspots would cause the heating function to fail quickly.

To determine the influence of spray angle on the dielectric strength of the insulation coating, a mild steel substrate C45 U with dimensions of $30 \times 25 \times 5 \text{ mm}^3$ was coated. In this case, only the bond coat and base insulation were applied. The nickel chromium bond coating was applied with a perpendicular spray angle, using the parameters as previously listed, Table 2. The parameters used to apply the aluminium oxide insulation coating were also listed, Table 2. It was applied with the same spray angle variation as described previously, Table 1. For all specimen, the gun was rotated to adjust the spray angle while keeping the distance to the

specimen constant, in order to better observe the application process in the real-world application case.

In the measurement of dielectric strength, two test tips are applied to the specimen, one to the substrate and one to the as-sprayed rough surface of the insulation coating. The voltage is then increased until a leakage current can be measured. During the measurement, an alternating current was applied and the voltage was increased at 100 V/s until a current intensity of 0.001 A could be measured as leakage current. A total of three measurements were carried out at different spots per specimen in order to keep influences caused by roughness to a low level. The value of the lowest breakdown voltage was evaluated. This provides information on the dielectric strength of the specimen in relation to the thickness of the coating.

3 | RESULTS AND DISCUSSION

In the following chapter, the obtained results are presented. First, the influence of the spray angle variation on the properties of the titanium oxide/chromium oxide heating coating is discussed, followed by the aluminium oxide insulation coating.

3.1 | Deposition efficiency

The coating thickness as a function of the spray angle for the coating process of the titanium oxide/chromium oxide heating coating decreases with increasing deviation of the spray angle, Figure 3. Using the coating thickness, the deposition efficiency can be derived, since the number of transitions during the coating process was kept constant.

TABLE 2 Parameter set for the heating coating system.

Feedstock material	NiCr20	Al ₂ O ₃	TiO _x /Cr ₂ O ₃
Fraction	-53 + 25 μm	-45 + 22 μm	-25 + 5 μm
Nozzle diameter [mm]	9	9	9
Primary gas Ar [SLPM]	70	60	60
Secondary gas H ₂ [SLPM]	0	6	6
Current [A]	400	450	450
Stand-off distance [mm]	120	120	120
Meander width [mm]	5	5	5
Robot velocity [mm/s]	800	1000	1000
Carrier gas Ar [SLPM]	4.5	5.5	7.5
Powder feed rate [g/min]	31.0	21.1	23.6
Transitions	4	9	13

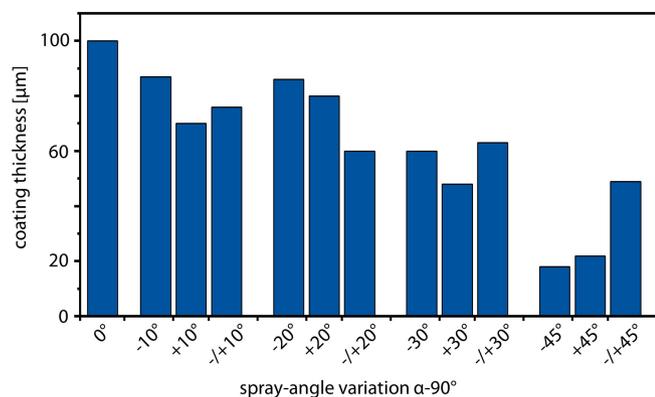


FIGURE 3 Heating coating thickness as a function of the spray angle deviation from the perpendicular angle.

Using the perpendicular spray angle as reference, the coating thickness of the heating coating results $s = 100 \mu\text{m}$, whereas the coating thickness decreases with increasing deviation of the spray angle. At a deviation of $\alpha = 10^\circ$, the average coating thickness is $s = 78 \mu\text{m}$, while at a deviation of $\alpha = 20^\circ$, the average thickness is $s = 75 \mu\text{m}$. The value decreases more significantly at $\alpha = 30^\circ$ to an average of $s = 57 \mu\text{m}$, and especially at a deviation of $\alpha = 45^\circ$, the average thickness decreases to $s = 30 \mu\text{m}$. It is evident from the results that the coating thickness decreases with increasing deviation from the perpendicular spray angle. Thus, it can also be concluded that the deposition efficiency is reduced in a similar manner. Up to a deviation of $\alpha = 20^\circ$ from the perpendicular spray angle, the decrease in deposition efficiency is still within an acceptable range. However, beyond this point, the deposition efficiency decreases significantly. It is described that the coating thickness reduction at higher spray angle deviation is depending on the decrease of the normal component of the particle velocity in relation to the substrate surface [15].

3.2 | Resistivity

The influence of the spray angle on the resistivity of the heating coating has also been investigated, Figure 4. The results demonstrate a significant effect of the spray angle on this property of the coating. As the spray angle increases, the resistivity of the coating also increases.

The reference specimen with a perpendicular spray angle shows a similar value of $\rho = 0.5 \Omega\text{mm}$, which is similar to the ones observed in previous studies [5, 16]. This value can be maintained up to a deviation of $\alpha = 20^\circ$ from the perpendicular spray angle, with only a slight increase in resistivity. The dragging or stabbing direction of the plasma spray jet has a small effect on this property. However, at a spray angle of $\alpha = 45^\circ$, the electrical

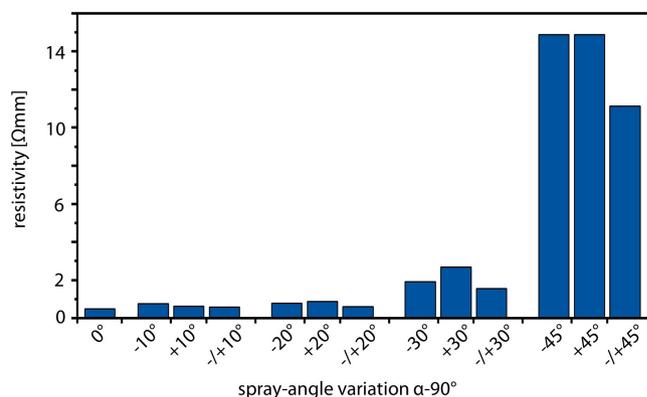


FIGURE 4 Resistivity of titanium oxide/chromium oxide heating coating as a function of the spray angle deviation from the perpendicular spray angle.

resistance of the heating coating increases sharply and the resistivity can be determined up to $\rho = 14.9 \Omega\text{mm}$. When determining the resistivity, the thickness of the coating is taken into account, but the investigation is remarkably influenced by the roughness of the coating. This effect is particularly evident for low coating thicknesses and affects the determination of the resistivity.

The variation of the spray angle is associated with an increase in the distance that the spray particles must travel before reaching the substrate. The longer distance causes the plasma jet to mix more with the surrounding atmosphere, resulting in a change in the sub-stoichiometry of the titanium oxide/chromium oxide coating, as the particles are more susceptible to oxidation. This, in turn, affects the resistivity of the specimen. The longer distance also reduces the particle velocity, leading to a decrease in deposition efficiency.

3.3 | Heating cycle test

This study presents selected thermography images of the heating coating systems, Figure 5. The reference specimen applied at a perpendicular spray angle is depicted in a). In addition, b) shows the specimen with a variation of $\alpha = 10^\circ$, c) with $\alpha = 20^\circ$ and d) with $\alpha = 30^\circ$ spray angle variation. The specimens coated at a spray angle of $\alpha = 45^\circ$ could not be heated, as the high electrical resistance of these specimen meant that the available power source was not sufficient to heat the specimen adequately to the target temperature of $T = 150^\circ$. Only temperatures below $T = 70^\circ\text{C}$ could be reached.

Upon examination of the thermographic images, it can be observed that the temperature fields of the heating coating are quite similar. None of these exhibit any hotspots. This indicates that the heating coating remains functional under different spray angles. One noticeable

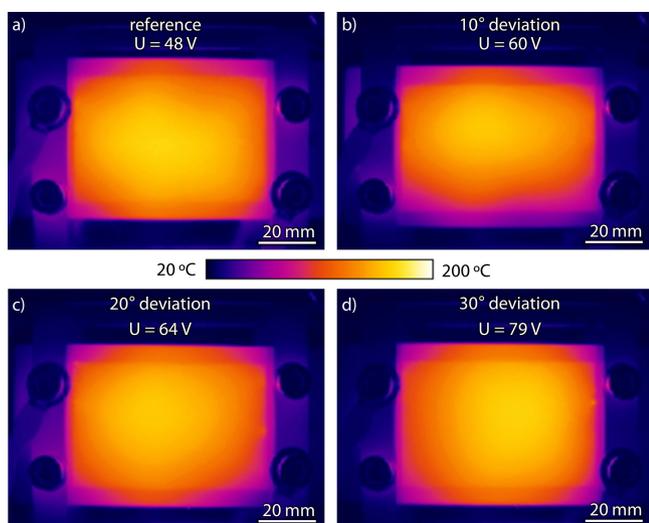


FIGURE 5 Thermographic images of the heating behaviour of the specimens with a) reference b) 10° c) 20° d) 30° spray angle variation.

finding from the investigation on the heating cycle test bench was that a higher voltage had to be applied to achieve the target temperature as the deviation from the optimal perpendicular spray angle increased, as the voltage for each specimen, Figure 5. This is partially due to the higher resistivity of the heating coating. This aspect should be considered when transferring the heating coating system, particularly with regard to the dielectric strength of the insulation coating.

The specimens with a spray angle deviation from the perpendicular angle of 20° were considered separately, Figure 6. In a) the dragging movement, in b) the stabbing and in c) the alternating movement of the jet during the coating process are shown. Again, very similar thermographic images can be seen. Also, the applied voltage for heating the specimen shown remains almost the same.

This leads to the conclusion that the movement direction of the particle jet, whether it is dragging, stabbing or alternately dragging/stabbing, does not have a

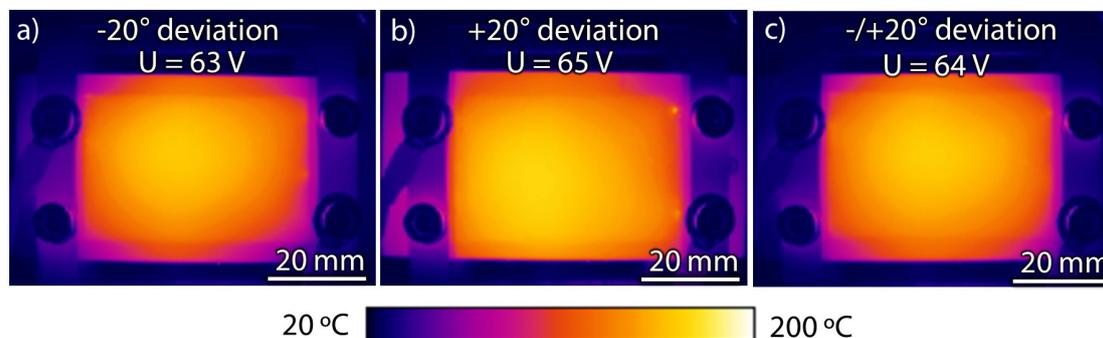


FIGURE 6 Thermography images of the heating behaviour of the specimens with a) -20° b) +20° c) +/-20° spray angle deviation.

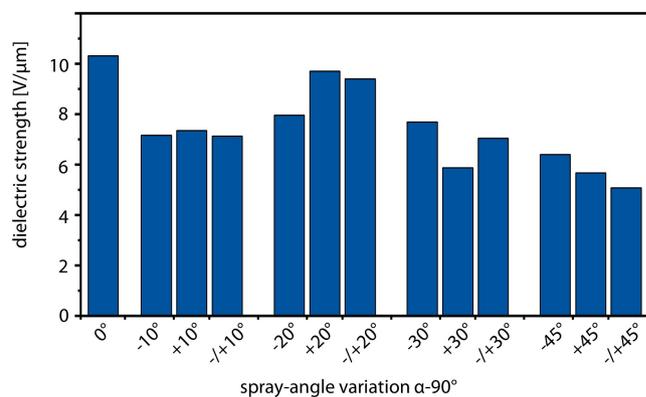


FIGURE 7 Dielectric strength of insulations coating as a function of the spray angle deviation from the perpendicular angle.

significant effect on the coating of the heating coating. This is an important finding for the deposition of the heating coating in application-oriented plastic injection moulding tools. When transferring the heating coating system to industrial tool moulds, the movement direction can be neglected.

3.4 | Dielectric strength

The dielectric strength of aluminium oxide insulation coating as a function of the spray angle was examined, Figure 7. This property is also affected by the spray angle and decreases with increasing spray angle deviation from the perpendicular angle.

With a perpendicular spray angle, the coating achieves a dielectric strength of $E_d = 10.3 \text{ V}/\mu\text{m}$. This value is comparable to the achieved dielectric strengths for thermally sprayed heater coatings with SPS-sprayed insulation coatings [17]. However, this property also tends to reduce with increasing deviation from the ideal spray angle. At a spray angle of $\alpha = 45^\circ$, the coating achieves a dielectric strength of only $E_d = 5.1 \text{ V}/\mu\text{m}$. Notably is the just slightly lower dielectric strength of two coatings with a spray angle variation of $\alpha = 20^\circ$ compared to the

reference coating. In general, the decrease in dielectric strength means that a thicker coating must be applied to enable comparable voltage without breakdown. This must be considered when transferring the entire heating coating system to prevent the current intended for heating the heating coating from flowing into the injection moulded part or the mould.

4 | CONCLUSION

The spray angle was varied in the atmospheric plasma spraying process for titanium oxide/chromium oxide heating coating and aluminium oxide insulation coating application for heating coating systems. The influence of the spray angle deviation on the properties of the respective coatings is presented below:

- Decrease in the deposition efficiency with increasing deviation from the perpendicular spray angle
- Small increase in the resistivity of the titanium oxide/chromium oxide heating coating with increasing deviation up to $\alpha = 30^\circ$. At $\alpha = 45^\circ$ a significant increase was measured.
- Uniform temperature distribution within the heating coating despite spray angle variation. However, a higher voltage had to be applied for higher spray angle deviations to achieve same heating power.
- The movement direction of the plasma jet, whether dragging, stabbing or alternating has a barely visible influence, especially on the heating behaviour.
- Decrease in the dielectric strength of the aluminium oxide insulation coating with increasing deviation from the ideal spray angle.

Overall, it is likely possible to transfer the heating coating system to complex part geometries. However, care must be taken to ensure that the spray angle does not deviate too much from the perpendicular impact behaviour. Furthermore, it must be ensured that the coating thickness can be kept constant over the entire coating surface.

Further research will be conducted to determine how the functionality of a heating coating system is affected when the spray angle varies within one coating. In addition, the influence of the spray angle on the roughness of the coatings is investigated. Moreover, the radius sizes on which the heating coating system can still be transferred while maintaining its functionality, will be investigated. This is particularly interesting for the transfer to real parts in plastic injection moulding.

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CONFLICT OF INTEREST STATEMENT

The authors declare no financial or commercial conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request on [http://hdl.handle.net/using the persistent identifier \(PID\): 21.11102/d066666a-774c-49e3-aadb-5108fc4ea07c](http://hdl.handle.net/using-the-persistent-identifier-(PID):21.11102/d066666a-774c-49e3-aadb-5108fc4ea07c).

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