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# Increasing the energy absorption capacity of structural components made of low alloy steel by combining strain hardening and local heat treatment

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**Abstract**

Modern high and ultra-high strength steels often require extensive alloy concepts and complex processing routes. To tailor the properties of low alloy steel accordingly, strain hardening combined with a subsequent local heat treatment presents a promising alternative. As a result, the final annealing step of the whole steel strip after cold rolling can be omitted. This process combination can be used to locally increase the formability of semi-finished parts as well as to improve the functionality of final parts. In this work, local heat treatment strategies are applied to increase the energy absorption capacity of a structural component. A high strength low alloy steel is strain hardened by cold rolling and heat-treated locally via laser irradiation. To identify suitable parameters for the laser heat treatment, the material is subjected to a short time heat treatment followed by a tensile test in a dilatometer. The determined mechanical properties are used for an FE study of a crash test. The FE model is used to develop potential local heat treatment strategies and to evaluate their crashworthiness. To validate the model, the developed heat treatment strategies are applied on real crash boxes. In dynamic impact tests, it is shown that the combination of strain hardening and local heat treatment can be used to improve the energy absorption capacity compared to a globally heat-treated crash box and to control the crash behaviour of structural components.


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*Keywords:* crashworthiness; dynamic crash test; lightweight; local laser heat treatment; tailor heat-treated blanks

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## 1. Introduction

Current lightweight design strives for high and ultra-high strength steels. However, high strength often involves a limited formability, which causes difficulties in production or final application [1]. To maintain the advantages of a high strength, the approach of 'Tailor Heat-Treated Blanks' (THTB) is to restore the formability locally prior to forming operations [2]. The critical areas of the blank are heat-treated, while the rest remains at high strength. In contrast to temperature assisted forming processes, the subsequent forming is typically performed at room temperature. This concept can either be used to increase the formability of semi-finished parts or to improve the functionality of the final part. As a result, THTB show a property distribution that is adjusted at best to the function of the final part. In preliminary work, a tailored heat treatment was successfully applied to improve the crash behaviour of a structural component made of strain hardened high manganese TWIP steel [3]. Such advanced high strength steels often require extensive alloy concepts combined with complex processing routes [4].

In this work, the THTB approach in combination with strain hardening is applied on a structural component made of low alloy steel to present an economic alternative to advanced high strength steels. While the local heat treatment pattern of the previous work [3] was determined based on the experimental results, this research uses an FE study to investigate numerically potential local heat treatment strategies. The goal is to develop an FE model that allows for the evaluation of the energy absorption in a crash test and to validate both methodology and model via experiments.

The investigated material is a micro-alloyed high strength low alloy (HSLA) steel. It is especially used for lightweight design applications, such as structural components in cars, due to its high yield stress. Increasing the yield stress further by strain hardening via cold rolling, enhances the energy absorptivity in areas of the structural component which are subjected to relatively low strains. Areas in which high strains occur might suffer from a lack of formability and hence are prone to cracks. Accordingly, these critical areas shall be locally softened by a laser heat treatment. To identify the influence of the heat treatment parameters on the material properties, the strain hardened material is subjected to a short time heat treatment using a dilatometer. The influence of the heat treatments is evaluated via tensile tests and microstructural investigations. The material data determined for different temperatures is used for an FE simulation of a crash test. This FE model allows for evaluating the crashworthiness by means of the energy absorption capacity and is used to develop potential local heat treatment strategies. The numerically designed heat treatment strategies are applied on crash boxes via laser irradiation followed by a high-speed impact test to validate the crashworthiness. Finally, the FE model is used to derive further options for an improvement of the crash behaviour of structural components.

## 2. Experimental and numerical investigations

### *2.1. Material and identification of heat treatment parameters*

The HSLA steel 1.0986 was cold rolled as strip from 4.0 mm to 1.6 mm. No final heat treatment was applied. The height reduction of 60 % leads to a significant strain hardening and hence increases the potential of a local heat treatment. To determine an appropriate temperature range for the laser heat treatment, heat treatments with different maximum temperatures ranging from 650 °C to 1200 °C were applied using a dilatometer (DIL 805A/D, co. TA Instruments). Similar to the characteristics of a laser heat treatment, each heat treatment consists of a linear heating and exponential cooling rate. The samples are heated inductively under high vacuum with 50 °C/s up to the respective maximum temperature, where the temperature is kept for 2 s. Using an inert gas, the temperature is reduced exponentially within two minutes down to 40 °C. The resulting mechanical properties were tested under quasi-static loading using the tensile test device of the dilatometer. The microstructure was analysed by light optical microscopy.

### *2.2. Dynamic impact tests*

Crash tests of structural components are used to evaluate their deformation behaviour under dynamic loading. In this case, a crash box, which is often used to compare different materials used for structural components, is chosen.

To validate the influence of the local heat treatment strategies on the crashworthiness, three different types of hexagonal crash boxes were manufactured: Two locally heat-treated crash boxes (Fig. 2b-c) are compared to a fully recrystallised crash box. The crash boxes are 275 mm high and 80 mm in diameter. Each crash box consists of two half shells that were laser-welded together. In case of the locally heat-treated crash boxes, cold rolled sheets were heat-treated according to the numerically developed patterns (see section 3.2). The local heat treatment was performed at a feed rate of 250 mm/min and a temperature of 1100 °C according to the results from the dilatometric study (see section 3.1). The laser beam width of the fibre-coupled diode laser (Laserline LDF 12.000-100) was set to 10 mm to reproduce the pattern properly. Afterwards, the sheets were roller levelled to eliminate the distortion resulting from the thermally introduced residual stresses. The plane sheets were then bent into half shells. Instead of a laser heat treatment, the sheets for the fully recrystallised crash boxes were recrystallisation annealed by radiant heat in a furnace under inert gas atmosphere. The crash tests were performed at a test facility of the Forschungsgesellschaft Kraftfahrwesen mbH (fka). The edges of all crash boxes were bent alternately to the inside and outside prior to the tests. This predetermines the bulge direction of the first fold and hence serves as geometrical trigger since the folds of one level bulge ideally alternating to the inside and outside. For all crash boxes, a test weight of 251 kg was dropped from a height of 5 m. This results in an impact velocity of about 36 km/h and an impact energy of approx. 12 kJ.

### *2.3. FE study for determining local heat treatment strategies*

The goal was to implement a simple FE model of a dynamic crash test which allows for a qualitative comparison of different local heat treatment strategies. The crash test was modelled using the software LS-DYNA with an explicit solver. For the hexagonal crash box, shell elements with reduced integration and an edge length of 3 mm were used. To simulate the geometrical trigger, the upper row of nodes is alternately displaced to the inside and the outside at its edges. An elastic-plastic material model is applied. The flow curves were determined based on the performed quasi-static tensile tests and extrapolated according to Hollomon. To provide an FE model which can easily be applied for industrial purposes, the model is based on commonly accessible material data such as tensile test data. Since the focus is to model areas of different strength levels within a crash box and to compare the crash behaviour of these crash boxes amongst each other, strain rate effects were neglected and a simple extrapolation approach was used. Analogously to the real experiment, the lower 25 mm of the crash box were fixed to model the clamping. The drop hammer is discretised as rigid plate and crushes the crash box with a constant velocity. The simulation is run up to an absorbed energy of 12 kJ. For the later comparison, the final height of the crash box is defined according to the experimental result.

## 3. Results and discussion

### 3.1. *Material properties in dependence of pre-strain and heat treatment*

Since the micro-alloyed HSLA steel is ferritic, recovery, recrystallisation and phase transition can be used as softening mechanisms. Additionally, solving temperatures of the strengthening carbides and nitrides are considered. Fig. 1a shows a selection of the mechanical properties tested under quasi-static loading. Due to the micro-alloying elements, a noticeable softening occurs after the short-term heat treatment at 800 °C. Up to a maximum temperature during the heat treatment of 1100 °C, the discontinuous yield stress vanishes and the formability increases while the strength decreases. At a temperature of 1150 °C, the formability decreases again. This observation is confirmed by the microstructural investigation shown in Fig. 1b: The flat grains, which stem from the cold rolling process, transform between 900 °C and 1100 °C into a globular microstructure. At 1150 °C the transformation into a lancet-like microstructure begins, which indicates a bainite or martensite formation. Comparing the as cold rolled material to the material heat-treated at 1100 °C, the ultimate tensile strength can be reduced from 1040 MPa to 658 MPa while at the same time the ultimate elongation is increased from 10 % to 24 %. Only by a complete recrystallisation annealing in a furnace, the strength can be reduced further down to 551 MPa and the ultimate elongation reaches almost 28 %.

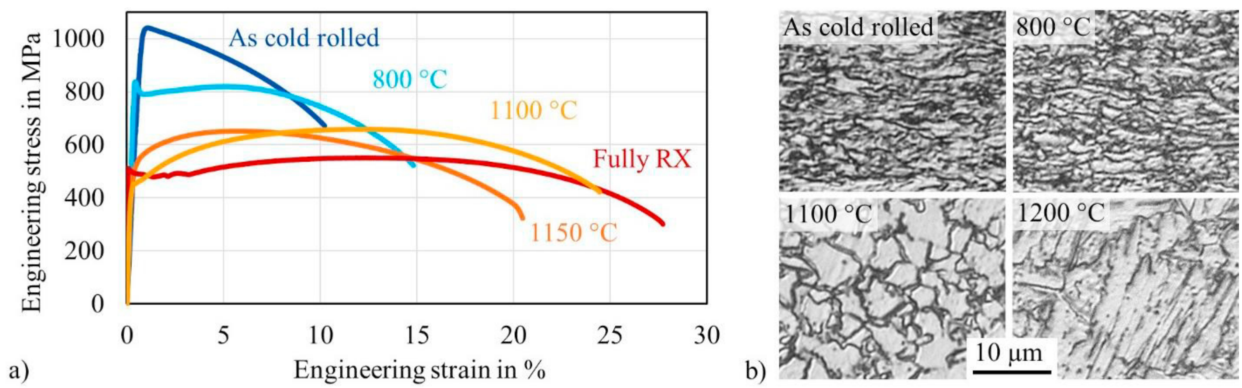



Fig. 1. Selected tensile test results (a) and microstructure (b) of 60 % cold rolled HSLA steel 1.0986 as cold rolled and after heat treatments at different maximum temperatures in the dilatometer compared to the fully recrystallised (RX) material.

### 3.2. Local heat treatment strategies

To model a locally heat-treated crash box, zones of two different strength levels were implemented. The hard zone represents the material as cold rolled, whereas the soft zone describes the heat-treated material. To validate the general methodology and the FE model, a local heat treatment pattern based on the strain distribution was chosen. In Fig. 2a, the simulated plastic strain of a crushed crash box, which only consists of a hard zone, is projected onto the unfolded crash box. The highest strains occur along the edges of the crash box. Hence, as a first simple pattern, the crash box is provided with a straight soft zone at its edges to approximate the strain distribution (Fig. 2b). Since the major part of the strains along the edges are higher than 20 %, the flow curve of the material heat-treated at 1100 °C is chosen for the soft zone to provide the necessary formability. For the second pattern, the soft zone displays the wavelike strain distribution along the edges more precisely (Fig. 2c). All areas along the crash box edges showing a plastic strain over 10 % were defined as soft zone. This limit was set, since the cold rolled specimen failed at an ultimate elongation of ~10 % in the tensile test. The remaining areas were defined as hard zone. Because of the different zones, the resulting folding behaviour and hence the strain distribution changes slightly in the simulation. Consequently, the soft zone had to be adjusted iteratively until it matches the strain distribution.

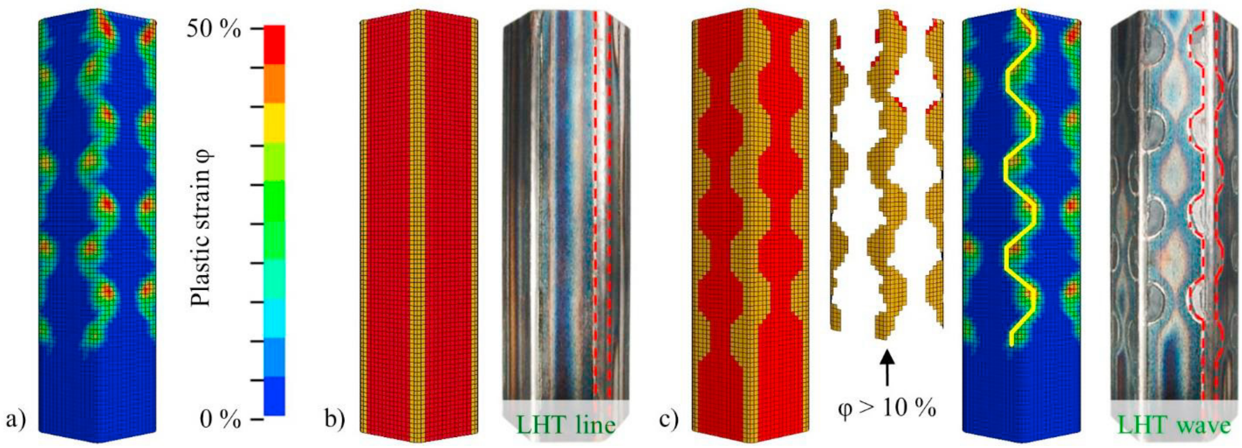



Fig. 2. (a) plastic strain of the crushed crash box projected onto the original crash box; modelled and real crash box with local heat treatment pattern (b) with straight soft zone at edges (LHT line) and (c) with strain-adapted wavelike soft zone (LHT wave).

### 3.3. Crashworthiness and model validation

To compare the different types of crash boxes with each other, the deformation paths which were necessary to absorb the impact energy are evaluated. The absorbed energy can be derived from the respective impact force and deformation path. The shorter the deformation path, the higher the resulting energy absorption capacity. The first local heat treatment strategy (LHT line) shows the highest reduction of the deformation path compared to the fully recrystallised crash box from 166 mm to 119 mm (Fig. 3). Applying the wavelike pattern (LHT wave), the deformation path is reduced to 143 mm. This can be attributed to its higher ratio of soft zone to hard zone compared to LHT line and hence a lower energy absorption capacity in highly strained areas. The corresponding high-speed recordings of the LHT wave experiment show the more important effect of this pattern: The folding occurs first in the soft zone which was also predicted by the simulation. This can be used to control position as well as distance of the folds. The numerically calculated energy absorption of LHT wave differs by 7 % from the experiment. The highest deviations to the experiment can be observed for the fully recrystallised crash box. Due to the material-related assumptions in the FE model, the results do not match perfectly. However, the folding behaviour, i.e. position and shape of the folds, as well as the differences in energy absorption are described sufficiently to develop an improved local heat treatment.

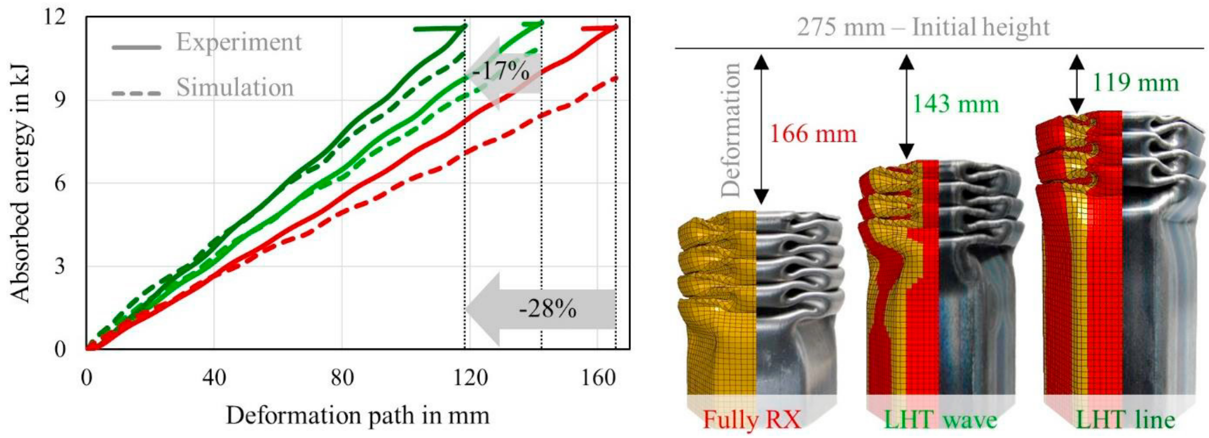
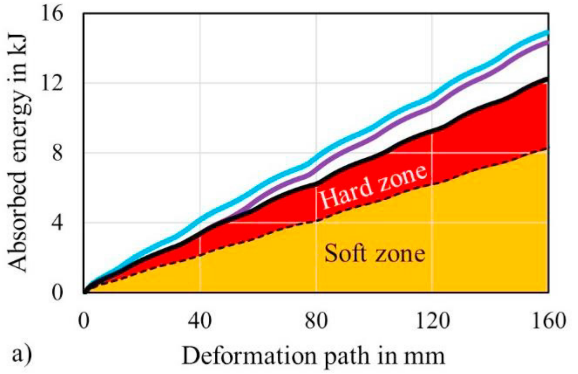



Fig. 3. Comparison of the absorbed energy per deformation path of the fully recrystallised (RX) and the locally heat-treated crash boxes (LHT wave and LHT line) in simulation and experiment.

### 3.4. Improvement of local heat treatment strategy

The dynamic impact tests have shown that the LHT wave pattern cannot reveal its advantages compared to the simpler LHT line pattern for this HSLA steel. However, the approach of the strain-adapted wavelike local heat treatment is still relevant for materials or strain hardening rates where the crash box cannot be crushed without cracks [3]. For the design of structural components, it is important to be able to predict and hence control the crash behaviour. The formation of cracks is an instable and non-predictable failure mode, which limits the formation of regular folds. An adapted local heat treatment cannot only prevent cracks but also allows for controlling the position of the folds. Consequently, the question arises, how the energy absorptivity of the LHT wave pattern can be increased further. The FE simulation displays that this soft zone which refers to 42 % of the elements absorbs almost 70 % of the total energy (Fig. 4a). Hence, the main energy is absorbed by the edges of the crash box where a doubled folding takes place. To increase the energy absorptivity further, it has to be focused on this region. Initially, it was assumed that in this region a preferably high formability is required to prevent the crash box from failure, which resulted in a heat treatment of 1100 °C. The experiments, however, showed no signs of cracks also in the as cold rolled areas. Hence, a local heat treatment at a significantly lower temperature might still be sufficient to control the crash behaviour. For a local heat treatment at 800 °C, the numerical simulation shows that the energy absorbed over a fixed deformation path of 160 mm can be increased to 14.9 kJ. The flip side of a crash box with higher strength is, however, the initial impact force which also rises (Fig. 4b). Since cars are designed with ascending collapse loads, a too high initial impact force of the crash boxes which are located in the front of the car may damage the structural components behind. To still benefit from the higher energy absorptivity, the approach is a crash box with a graded local heat treatment pattern as depicted in Fig. 4c. The upper part is subjected to a laser heat treatment at 1100 °C to reduce the initial impact force, while the lower part is heat-treated at 800 °C. This leads numerically to an initial impact force which is reduced by ~15 % compared to the non-graded crash box locally heat-treated at 800 °C, while the absorbed energy remains above 14 kJ. Comparing the graded to the LHT line crash box, absorbed energy and initial impact force are on the same level.




b)

| | Local heat treatment | Absorbed energy | Initial impact force |
|---|---|---|---|
| wave | 1100 °C | 12.2 kJ | 249.0 kN |
| | 800 °C | 14.9 kJ | 325.6 kN |
| | Graded | 14.3 kJ | 277.7 kN |
| line | 1100 °C | 14.5 kJ | 273.1 kN |

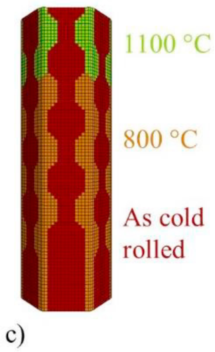



Fig. 4. (a) numerically calculated absorbed energy per deformation path of differently locally heat-treated crash boxes; (b) overview of absorbed energy and initial impact force depending on the local heat treatment; (c) design of a graded crash box.

## 4. Conclusion and outlook

The application of the presented process combination of strain hardening and local heat treatment turns the low alloy steel 1.0986 into a competitive alternative for structural components compared to costlier high strength steels. By implementing an FE model with material data from tensile tests, it was possible to quickly determine suitable local heat treatment strategies and to predict the approximate energy absorptivity of the material. The dynamic crash tests confirm that the combination of strain hardening and local heat treatment can be used to improve the crash behaviour of structural components and to influence the folding behaviour. The energy absorption capacity increases with the strain hardened part of the crash box. Adapted local heat treatment strategies help to define the initial impact force and control the position of the folding. To reduce the initial force maximum during the impact, an axially graded heat treatment is recommended. In future work, the developed FE model can be used to optimize the local heat treatment strategies further, e.g. aiming at a smaller distance of the folds to increase the energy absorptivity per space.

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