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Improving the crash behavior of structural components made of advanced high strength steel by local heat treatment

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Abstract. High manganese TWIP steel belongs to the second generation of advanced high strength steels. During the production of strip material, the microstructure and hence the mechanical properties of TWIP steel can be adapted to the specific needs of crash relevant structures. Whereas typically the whole steel strip is heat-treated after cold rolling, a local heat treatment can be applied to tailor the properties accordingly. In this work, a method is presented to identify a suitable process window for the local laser heat treatment of TWIP steel. The material is strain hardened and afterwards heat-treated at various temperatures for a short time. The influence of the respective heat treatment on microstructure and mechanical properties is evaluated and the most appropriate heat treatment is then reproduced using laser heating. To verify the effect of a local laser heat treatment at a structural component, crash boxes with different heat treatment patterns were produced and tested. The dynamic crash tests show that the local heat treatment can be used to improve the crash behavior of structural components. In addition, their deformation path can be influenced by using adapted heat treatment patterns and the crash behavior can be controlled.

1. Introduction

Advanced high strength steels (AHSS) have a great potential as lightweight material in the automotive industry compared to alternative materials as aluminum, plastics or carbon fiber reinforced plastics [1]. Strengths in the range of 1300-1500 MPa allow for the use of reduced sheet thicknesses and hence a weight saving of 30-40 % [2]. However, high strengths generally affect the formability. This complicates the processing of these steels and makes especially the cold forming difficult [3]. To still benefit from the high strength, the formability can be restored locally prior to the forming operation. The sheet metal is heat-treated within the areas prone to failure, while the rest remains at high strength. The subsequent forming can be performed at room temperature. The resulting ‘Tailor Heat-Treated Blank’ (THTB) shows a property distribution that is adjusted at best to the function of the final part [4].

Austenitic high manganese Twinning Induced Plasticity (TWIP) steel is part of the second generation of AHSS. It shows excellent crash behavior due to its high work hardening rate and hence is suitable for the use in structural components [5]. However, due to its low initial yield stress, TWIP steel cannot compete with industrially used dual phase steel DP800 in dynamic collapse tests [6]. Hence, the approach of a tailored heat treatment can be used to improve the crash behavior of structural components made of high manganese steel.
In this work, the high manganese TWIP steel Fe-28Mn-0.3C is investigated. A method is developed to identify suitable parameters for the local laser heat treatment: The material is strain hardened by cold rolling and the effect of different heat treatments on its microstructure and the resulting mechanical properties is evaluated via dilatometric experiments. The most promising heat treatment is then reproduced via laser heating. To investigate the effect of a local laser heat treatment on the crash behavior of a structural component, crash boxes with two different heat treatment patterns are manufactured. The patterns consist of alternating strain hardened and softened zones. Dynamic impact tests are performed to test the energy absorption capacity. The resulting energy-displacement curves are used to compare the different heat treatment patterns and assess their influence on the crashworthiness.

The goal is to show for a structural component that it is possible to improve and locally tailor the mechanical properties of AHSS based on a shortened process chain including local laser heat treatment, and thus, to reveal completely new design options. This yields the following research questions:

- How can the microstructure and mechanical properties of high manganese TWIP steel be influenced by a short-time (laser) heat treatment?
- Can the energy absorption capacity be increased by adapting the material properties in the different areas to the external loading condition during deformation?
- Does the deformation follow the pattern of softened and hardened zones?

2. Experimental work

2.1. Material and processing

The investigated Fe-28Mn-0.3C is a high manganese steel which forms twins during the deformation at room temperature. The TWIP behavior can be related to its stacking fault energy of 27 mJ/m² [7]. The material was produced at a lab-scale strip casting system of the Institute of Metal Forming (IBF) of RWTH Aachen University. The main advantages of twin-roll strip casting are the high cooling rates and the integrated forming process which enables a near-net-shape production of such high-alloyed steels. The applied process chain enables the production of high manganese TWIP steels with excellent mechanical properties compared to conventional strip production [8]. In table 1, the chemical composition of the cast strip is given.

### Table 1. Chemical composition of as-cast Fe-28Mn-0.3C-alloy in wt% according to optical emission spectrometry.

| Element (wt%) | Fe  | C   | Mn  | Al  | Si  | N   | S   | P   |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Cast strip   | Balance | 0.284 | 27.84 | 0.003 | 0.107 | 0.004 | 0.002 | 0.01 |

The strip cast and inline hot rolled material with a thickness of 1.5 mm was subsequently cold rolled to 1.1 mm. The height reduction of 25% strengthens the material effectively without eliminating its formability. Hence, the energy absorption capacity is increased while at the same time a sufficient formability of the strain hardened zones of the crash box is ensured. This facilitates a regular buckling during the crash test.

2.2. Dilatometric study

To identify a suitable temperature for the local heat treatment, different heat treatments with a maximum temperature ranging between 600 and 900 °C were applied using a dilatometer (DIL 805A/D, co. TA Instruments). Heating was carried out inductively under high vacuum. The heat treatment cycle is based on the general characteristics of a laser heat treatment, i.e. fast heating and exponential cooling rate. The used heating rate was 50 K/s, the holding time was set to 2 seconds and the cooling continues exponentially within two minutes down to 40 °C.

Then, the resulting microstructure was analyzed by means of electron backscatter diffraction (EBSD) at the Institute of Physical Metallurgy and Metals Physics (IMM) of RWTH Aachen University. The
mechanical properties under quasi-static loading ($\dot{\varepsilon} = 0.0025 \text{ s}^{-1}$) were investigated using the deformation device of the dilatometer.

### 2.3. Local heat treatment concepts

To investigate the influence of a local heat treatment on the crashworthiness of the work hardened high manganese steel, two different heat treatment patterns were applied onto the crash boxes. The first pattern (see figure 1a) stems from the regular folding which was observed in the crash tests of the fully recrystallized high manganese TWIP steel [6]. It is assumed that the buckling of the folds, once started, is a purely geometrical effect. The measured distance of the tips of the folds was 20 mm. Hence, every 20 mm a heat-treated zone of 5 mm width was applied. The interaction of strengthened and softened areas is supposed to be beneficial for the crashworthiness. While the strengthened areas are supposed to increase the energy absorption capacity, the softened areas allow for a stable deformation process in the highly strained tips of the folds.

In the second heat treatment pattern (see figure 1b), the distance of the heat-treated zones was increased to 30 mm. Here, it is tried to influence the natural folding behavior and to control where the folding occurs. It is expected that the folds form preferably in the softened areas.

![Figure 1](image_url)

**Figure 1.** Locally heat-treated crash boxes made of Fe-28Mn-0.3C (a) with heat-treated zones in 20 mm distance (pattern A), (b) heat-treated zones in 30 mm distance (pattern B), (c) hexagonal crash box geometry.

As depicted in figure 1c, hexagonal crash boxes were manufactured. The plane, 25 % cold rolled sheets were heat-treated at the Fraunhofer Institute for Laser Technology (ILT) in Aachen using a fiber-coupled diode laser (Laserline LDF 12.000-100). In addition to the described patterns, the bending edges were locally heat-treated to avoid failure and to facilitate accurate bending. The laser beam width was 7 mm to make sure that the bent length of 5 mm is completely heat-treated. The feed rate for all heat-treated zones was 500 mm/min and the applied temperature was approx. 900 °C according to the results from the dilatometric study (see chapter 3.1). After the heat treatment, the sheets had to be roller levelled to eliminate the distortion resulting from the thermally introduced residual stresses. For each crash box, two square sheets were bent and then laser-welded at the ILT.

### 2.4. Dynamic crash tests

Crash tests of individual components are used to evaluate their deformation behavior under dynamic loading. The crash tests were performed at a test facility of the Forschungsgesellschaft Kraftfahrwesen mbH (fka). For pattern A, a test weight of 250 kg was dropped from a height of 2 m resulting in an impact energy of approx. 5 kJ. The drop height of 2 m was chosen to be able to compare the test results to the previously performed experiments. However, it is assumed that the strain hardened crash boxes are able to absorb even more energy. To use the full capacity of pattern B, which stretches over the whole crash box, a drop height of 3 m was applied in this case. This resulted in an impact energy of 8 kJ.
3. Results and Discussion

3.1. Dilatometric heat treatment
Due to the high manganese content, the microstructure of Fe-28Mn-0.3C is austenitic at room temperature. Recovery and recrystallization are the only mechanisms that can restore the formability of the strain hardened strip during a heat treatment. The question is how the recrystallization proceeds at the investigated temperatures considering the degree of pre-deformation and the shortness of the heat treatment.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Microstructure of Fe-28Mn-0.3C. EBSD IPF mappings of the cross-section of (a) the as-cast and inline hot rolled strip and (b) the 25% cold rolled sheet after the short-term heat treatment at 900 °C.

The EBSD mapping of the hot rolled Fe-28Mn-0.3C shows the typical solidification structure of strip-cast material (see figure 2a). The large grains are elongated and aligned according to the heat flow. On the other hand, the processed sample shows deformation twins and slip bands resulting from cold rolling (see figure 2b). However, the strain hardened structure has mostly dissolved after the short heat treatment at 900 °C and the microstructure is partially recrystallized. The cold rolling with 25% height reduction is sufficient to trigger the recrystallization process, but non-recrystallized areas containing the initial hot strip microstructure are still apparent.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Tensile test results of (a) 25% cold rolled Fe-28Mn-0.3C after different short-term heat treatments in the dilatometer and (b) fully recrystallized Fe-28Mn-0.3C compared to the dual phase steel DP800.
Figure 3a shows the mechanical properties under quasi-static loading after cold rolling and heat treatments at various temperatures. The cold rolled strip has an ultimate tensile strength of 844 MPa and a total elongation of 7%. With advancing recovery and the onset of recrystallization, the strength decreases and the formability increases. After a heat treatment at 900 °C, the ultimate tensile strength equals the as-cast condition, i.e. 652 MPa [8]. The elongation, however, is with 39% more than half restored as the EBSD mapping already suggested. Based on the results gained from the dilatometric study a local laser heat treatment of 900 °C is applied to restore a sufficient formability.

From other experiments it is known that a height reduction of 50% in cold rolling is necessary to achieve a fully recrystallized microstructure during the short-time heat treatment at 900 °C. As aforementioned, the resulting formability of about 1% is not high enough.

3.2. Crashworthiness

The mechanical properties shown in figure 3b help explain why the DP800 outperforms the high manganese steel in the dynamic collapse test. The fully recrystallized Fe-28Mn-0.3C cannot absorb enough energy within the crash relevant strain level compared to the industrially used dual phase steel. Using cold working, the initial yield stress and hence the energy absorption capacity of the high manganese steel can be enhanced. However, sufficient formability still needs to be provided for a stable deformation during crash. Consequently, the local heat treatment patterns were applied to soften the crash box in its highly strained areas.

Figure 4 shows the results of the dynamic crash test of the locally heat-treated crash box according to pattern A compared to the DP800 and a globally heat-treated crash box, also made of Fe-28Mn-0.3C. The latter was fully recrystallized after cold rolling. As intended, the strain hardening combined with the tailored local heat treatment improves the crashworthiness of the high manganese TWIP steel effectively. The energy of about 5 kJ was absorbed in a deformation path of only 85 mm. The fully recrystallized crash box needed almost twice the length, 166 mm, to absorb the same energy. Due to the local heat treatment, the high manganese steel outperforms the dual phase steel, which has a deformation path of 140 mm. The high strength of the strain hardened zones enables to consume more energy during the crash test, while the softened zones with its low yield stress allow for a stable crushing.

The influence of the softened zones become even more pronounced for the heat treatment pattern B. As visible in figure 5, a periodic folding according to the alternating material properties was realized. The softened zones serve as preferred location for the formation of folds in case of both heat treatment patterns. In contrast to pattern A, here, the “natural” distance of the folds, which is assumed to be determined by a purely geometrical effect, is shifted to higher values. While for the crash box in fully
recrystallized condition a distance of 20 mm is observed, the distance of the folds could be successfully increased to 30 mm according to pattern B.

Both approaches reveal not only an enhanced crashworthiness but also completely new design possibilities for crash relevant structures based on local heat treatment. A locally heat-treated crash box with reduced sheet thickness absorbs the same energy compared to its fully recrystallized counterpart with thicker sheet. By decreasing the distance of the folds, more energy can be absorbed over the same length. Hence, lighter or smaller crash relevant structures can be applied to absorb the kinetic energy in case of a crash. Alternatively, the folding may be split in several predefined areas by introducing the softened zones discontinuously in the component.

Figure 5. Recordings of a high-speed camera during the crash test of the locally heat-treated Fe-28Mn-0.3C crash box with pattern B.

4. Conclusion
Due to its high work hardening rate, the investigated high manganese TWIP steel Fe-28Mn-0.3C promises a high energy absorption capacity in crash relevant components. The presented combination of strain hardening and local heat treatment makes use of the wide range of material properties of high manganese TWIP steel. In dilatometric experiments, it was shown that the recrystallization is triggered within a short-term heat treatment similar to laser heating.

By means of a tailored heat treatment the deformation behavior of crash boxes can be modified. On the one hand, the crashworthiness can be significantly improved by alternately introducing softened and hardened areas. Due to the higher formability within the softened areas, the crack formation is drastically reduced and a stable deformation progress ensured. As a result, the forming capacity of the material can be used to a larger extend and the energy absorption can be increased.

On the other hand, the local material softening serves to control and predict the crushing of a structural component. Both the distance of the folds as well as the preferred area of deformation can be predetermined by a local adjustment of the mechanical properties. Hence, crash relevant components can be designed and customized according to the constructive requirements. This demonstrates the great potential of a local laser heat treatment for the use of advanced high strength steels in lightweight design.

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