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The Deformation Behavior of Functionally Graded TWIP Steel under Monotonic Loading at Ambient Temperature

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A processing route for the generation of functionally graded parts from steels showing twinning-induced plasticity is proposed. The procedure employing pre-deformation and local heat treatment allows for tailoring local properties with a high degree of freedom. Quasi-static tension tests revealed that no process-induced drawbacks are present, so that functionally graded parts of unprecedented performance become feasible.

Keywords: High Manganese Steel; Microstructure; Recrystallization; Digital Image Correlation; Strain Gradients

The demand for high performance materials in many industrial branches has increased tremendously owing to the need for resource-efficient processes and components with improved performance. One of the technology leaders with regard to this aspect is the transportation sector, where resource efficiency is not only process related, but mainly linked to decreased fuel consumption. One of the keys to resource efficiency here is light-weight design, which can be achieved by several ways, amongst others by the use of materials of high specific strength [1–5]. Well-known light-weight metals are aluminum, titanium and magnesium [4], and fiber-reinforced polymers [5] are promising candidates, too. Yet, several drawbacks are linked to these groups of materials. In addition to cost and forming issues, shape tolerances and stiffness need to be mentioned here. Common steels do not suffer from these problems, but their specific strength is not high enough to allow for light-weight design. Consequently, new kinds of steels have been proposed within the last decades, combining high strength and good formability [1,2,6–8]. Dual-phase steels, complex-phase steels, boron alloyed steels for press-hardening processes and metastable austenitic steels showing transformation-induced plasticity (TRIP) [1–3] are now widely used for industrial applications. Another group of steels with

outstanding mechanical properties, that is, high ultimate strength and extreme ductility, are high manganese steels showing twinning-induced plasticity (TWIP) [6–11]. These steels developed at the end of the last century show twinning upon deformation hindering necking by local increase of strength. Tremendous hardening referred to as ‘dynamic Hall–Petch effect’ accompanies deformation at least in TWIP steels of commercial grain size [10,12]. TWIP and TRIP steels are somehow similar due to their alloying concepts, and the key parameter for the active deformation mechanism is the stacking fault energy, which can be tailored by alloying elements and deformation temperature [8,13].

The performance of components and materials can also be optimized by the gradation of the mechanical properties. One well-known example is tailored blanks, where sheets are stacked and joined such that plates of graded and optimized thickness become available [14,15]. Another possibility of the gradation of materials is the optimization of strength and ductility through local variation in microstructure [14,16]. By employing locally different time–temperature paths, local microstructures and eventually locally different properties can be achieved. However, tempering steels are very sensitive to embrittlement in certain processing

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windows [16], and thus, it is very difficult to obtain components with highly differing local properties without sacrificing properties in some parts of this component.

The present study reveals that it is possible to obtain high performance parts with steep functional gradients by local heat treatment of TWIP steel, and thus unites two aspects of light-weight design within one process. Based on a thorough investigation of the interaction between pre-deformation, heat treatment and microstructure evolution, parameters for gradation are established. The reliability of the new process is demonstrated by testing two different graded specimens.

A commercial X-IP™ 1000¹ TWIP steel was delivered in form of a blank from cold rolled sheet with a thickness of 1.6 mm. Samples with nominal gauge sections of 8 mm × 3 mm × 1.4 mm (miniature specimen), 85 mm × 10 mm × 1.4 mm and 100 mm × 35 mm × 1.6 mm were machined from the plate by electro-discharge machining. The loading direction of all samples coincided with the former rolling direction. In order to remove the machining-affected surface layer and to ensure a high surface quality, the small samples were ground mechanically down to a grit size of 5 μm. The mechanical properties were established using a Vickers hardness tester, a screw-driven and a servo-hydraulic test rig. Tension tests were conducted in displacement control with a rate of 2 mm min⁻¹. Testing of the miniature samples at room temperature employed a miniature extensometer directly attached to the sample. The tests of the functionally graded specimens were accompanied by *in situ* microscopy allowing for subsequent strain analyses by means of digital image correlation (DIC). Surfaces were pre-treated by sand-blasting, and images of the strained surfaces were taken in defined steps using a commercial 10.2 million pixel digital camera. DIC was conducted using VIC-2D from Limess Messtechnik. Details on the setup are presented in [18,19]. In order to investigate the recovery and recrystallization kinetics and the microstructural evolution of pre-strained X-IP™ 1000 TWIP steel, the following procedures were used: the miniature specimens were pre-strained to 40% and heat treated in vacuum for 30 min at temperatures ranging from 300°C to 1050°C in a commercial furnace. The functionally graded specimens were pre-strained as well and subsequently heat treated for 30 min in air using an induction heating system. Since all samples were post-treated by sand-blasting for subsequent strain analyses, the oxygen-affected layer got removed prior to mechanical testing. In order to allow for a local treatment of the samples, ferritic steel sheets of different sizes were mounted on the TWIP steel surfaces to act as a local heat source within an induction coil. Due to the much higher coupling of the magnetic field to the ferritic sheets, only these got heated up to the envisaged temperatures, the austenitic TWIP steel without ferritic sheets attached only

reached temperatures allowing for slight recovery. Temperature was measured and controlled via thermocouples mounted onto the ferritic sheets. Following heat treatment and mechanical testing, some of the specimens were thoroughly investigated by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The SEM was equipped with an electron backscatter diffraction (EBSD) unit. TEM samples were prepared by conventional twin-jet polishing using a 5% perchloric acid at a temperature of -40°C, and the same solution was employed for electro-polishing of the specimens characterized by EBSD. The SEM and the TEM were operated at 20 and 200 kV, respectively.

Figure 1 shows the monotonic stress-strain response of the differently treated miniature specimens. Obviously, the temperature of heat treatment has a significant impact on the microstructure evolution and mechanical behavior of the TWIP steel as has been shown before for similar steels by other authors [20–25]. In comparison with results shown for a very similar alloy by Bouaziz et al. [24,25], the thermal stability of the X-IP™ 1000 TWIP steel investigated in the present study seems to be slightly improved. This can be attributed to the higher amount of additional alloying elements in the present material [17], eventually stabilizing the microstructure. Following pre-straining, the samples show a significant increase in both hardness, as shown in the inset of Figure 1, and yield strength. The small change in hardness up to a heat treatment temperature of 600°C implies the presence of recovery only. The mechanically induced twins are thermally stable up to a temperature of 625°C as shown for a very similar alloy [24]. Consequently, the monotonic stress-strain behavior is altered only slightly, yield strength decreases by about 200 MPa when compared with the 40% pre-strained material without additional heat treatment; ultimate strength and elongation to failure still are similar. The major difference revealed from Figure 1 is the ability to show some hardening after the pre-deformation, which cannot be observed in the not heat-treated condition. This has been shown for a different TWIP alloy in [25]. An increase of temperature above a level of 600°C leads to a decrease of hardness indicating evidence of recrystallization. Above 700°C, the slope of the hardness curves changes again, indicating a region of significant grain growth. The monotonic stress-strain response changes accordingly. Increasing heat treatment temperatures lead to an increase of elongation to failure and a decrease of strength. Especially, the yield strength decreases tremendously, when the heat treatment is conducted above 600°C. A treatment at 650°C almost restores the properties of the as-received condition. A further increase of the temperature leads to maximum elongation to failure of about 100%, but at the same time to a significant loss in strength.

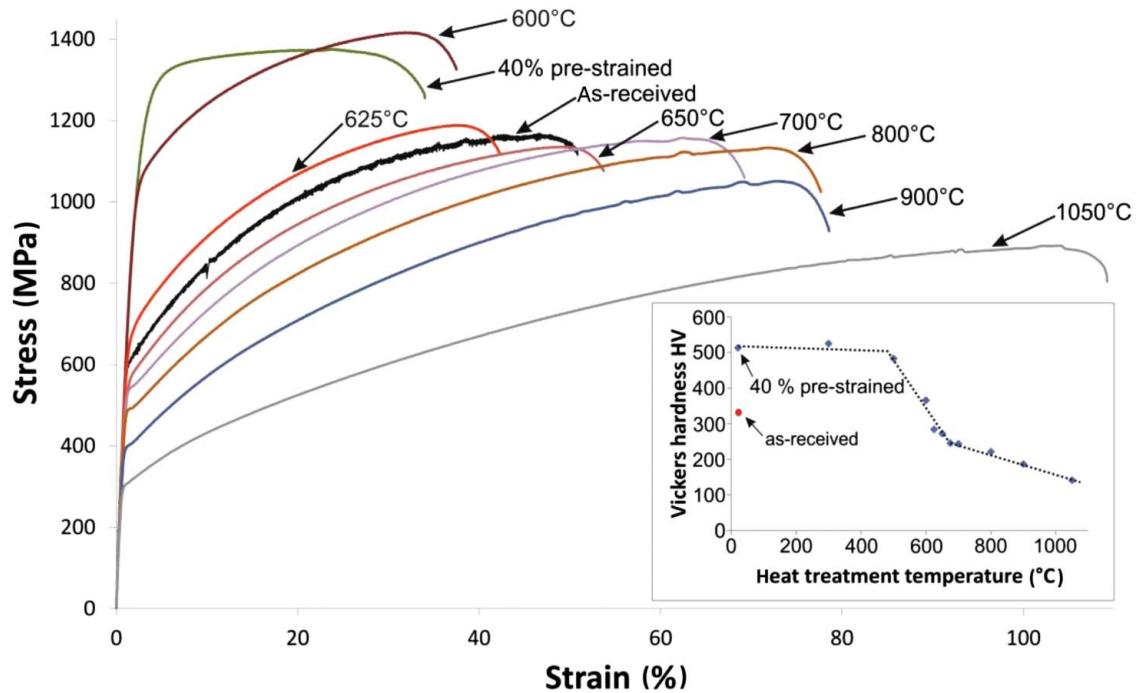


Figure 1. Monotonic stress–strain response of X-IPTM 1000 TWIP steel tested at room temperature (curve for the as-received material has been recompiled from [26]). All samples were pre-strained to 40% and heat treated for 30 min at the given temperature. The inset shows the corresponding evolution of the hardness.

Microstructure analyses using EBSD clearly lays out the reasons for the changes in mechanical properties. Following heat treatment at 600°C, the microstructure still is very similar to the pre-strained condition. Obviously, heat treatment up to a temperature of 700°C is capable in a full reestablishment of the initial microstructure, which features a mean grain size of about 5 μm [26]. Up to this temperature EBSD hardly detects changes in the microstructure, which are due to recovery and recrystallization. An increase of the heat treatment temperature to a level above 700°C leads to intense grain coarsening. The EBSD micrographs shown in Figures 2(b) and 2(c) clearly depict this tendency (the scale in Figure 2(c) is different for the sake of depicting more than a single grain). In how far deformation-induced twin structures within the grains get affected by heat treatment cannot be resolved clearly by EBSD, as can be seen from Figure 2. Thus, additional microstructure analyses by means of TEM have been conducted.

Figure 3(a)–(d) shows TEM bright field images of differently heat-treated samples. Following pre-straining to an elongation of 40%, the heavily deformed microstructure is characterized by a high density of twins and dislocations, respectively. This microstructure is similar to X-IPTM1000 strained to failure [26]. Following a heat treatment at 600°C, the microstructure still resembles the initially pre-strained condition (cf. Figure 3(a) and 3(b)). Consequently, only recovery is active up to this temperature. Following heat

treatment at 750°C, the microstructure is recrystallized to a high extend (Figure 3(c)), but still some areas are unaffected as indicated by deformation twins locally present. Further increase of the temperature leads to the evolution of a fully recrystallized microstructure with hardly any remaining deformation twins and dislocations (Figure 3(d)).

Based on the findings available in the literature for similar TWIP alloys [20–25] and the microstructural evolution presented in the present paper, deformation-heat-treatment procedures were developed in order to reveal that microstructurally graded specimens with tailored properties are feasible for the TWIP steel investigated. Figure 4(a)–4(c) shows an X-IPTM1000 sample incrementally strained up to a total strain of more than 300% at room temperature. The initial sample (Figure 4(a)) was strained up to 30% and then locally heat treated for 30 min at 750°C using ferritic sheets of 80 mm $\times$ 50 mm symmetrically fixed to the sample surfaces. The two other conditions depict the sample following accumulative total strains of about 150% (Figure 4(b)) and 300% (Figure 4(c)), respectively. Clearly, no failure is observed up to this point, indicating that the recrystallization treatment fully recovers the initial monotonic properties many times despite the presence of some micro-pores, which have been found on fatigue crack surfaces of pre-strained samples in a former study of the authors [27]. Using different parameters for mechanical testing and heat treatment, the same trends were found (not shown).

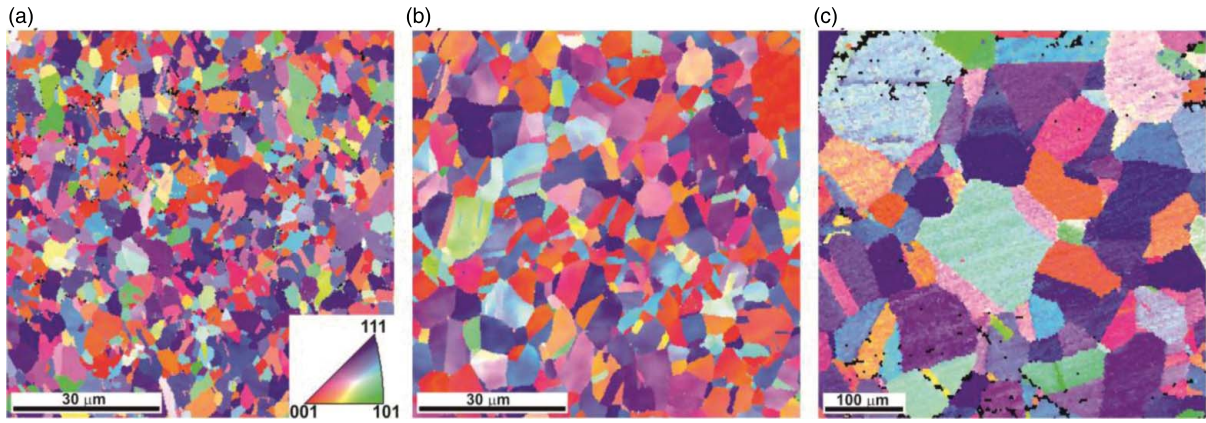


Figure 2. EBSD data showing the microstructures upon pre-straining and subsequent heat treatment for 30 min at (a) 700°C, (b) 900°C and (c) 1050°C. The scale in (c) is different in order to show more than a single grain.

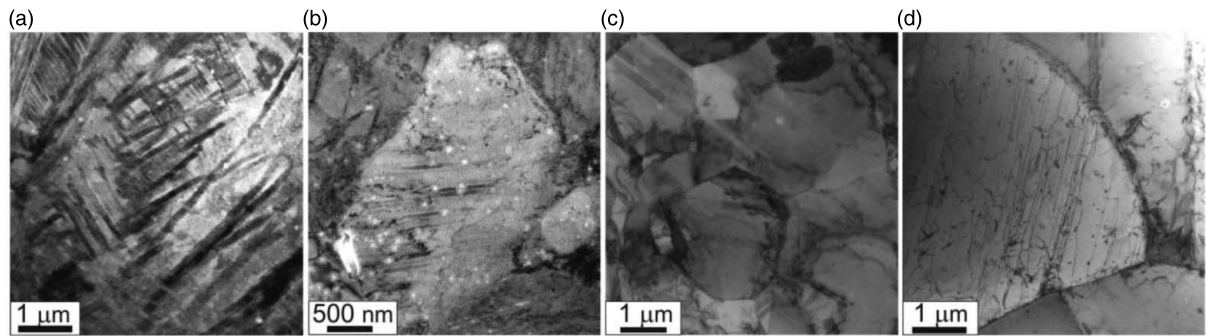


Figure 3. TEM bright-field images for samples (a) in the pre-strained condition and upon pre-straining and heat treatment for 30 min at (b) 600°C, (c) 750°C and (d) 900°C. For the sake of clarity, the scales are different.

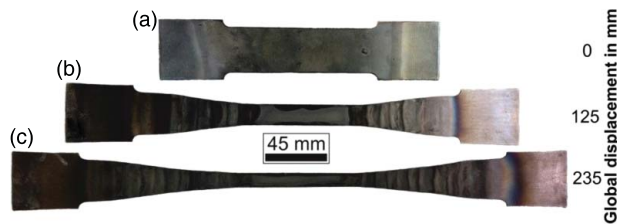


Figure 4. Incrementally deformed TWIP steel sample depicted for three different conditions: (a) in the as-received condition, and upon local deformation to about (b) 150% and (c) 300%.

A second heat treatment procedure aimed at the generation of a functionally graded TWIP steel specimen exhibiting different strains in different areas of the sample under constant loading of the gauge length. Thus, only small areas of the specimen were heat treated using a similar approach, that is, fixing small separate ferritic sheets in the gauge length. In order to obtain different temperatures in the single sheets, the setup was fixed within the inhomogeneous part of the magnetic field of the induction furnace. Each of the three pairs of ferritic sheets was measured by a thermocouple. Figure 5 shows the corresponding hardness evolution in the sample's gauge

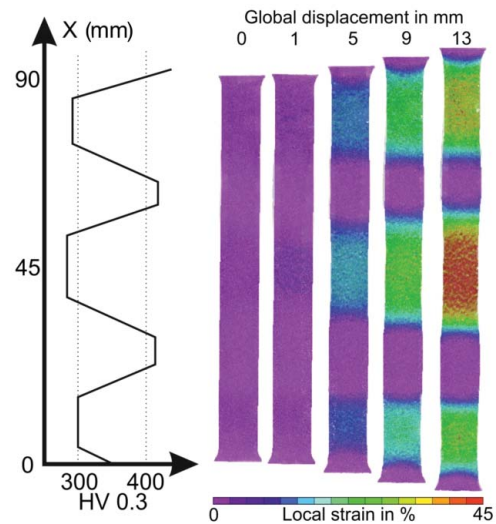


Figure 5. Hardness profile of a locally heat treated sample and evolution of local strains as determined by DIC in the functionally graded specimen at given global displacements.

length upon heat treatment. Obviously, the heat treatment led to significant differences of microstructure and eventually monotonic properties in the gauge length of the

sample. The subsequent tensile test revealed the impact of the microstructural gradation. The area of the sample treated at 750°C (middle section) showed the highest strains from the onset of deformation, but did not fail at any stage of testing. As can be deduced from the results shown in Figure 1, the 750°C treatment fully preserves the properties of the TWIP steel including the high hardening capability. Thus, early local plastic deformation leads to local dynamic strengthening which delays necking, as is the case in untreated TWIP steel. Consequently, the heat-treated area is able to compensate for the loss of strength until the strength is equal to the surrounding areas and the whole gauge length is deformed homogeneously again. Obviously, there is no tendency to form a brittle layer in any part of the sample. Such kind of local degradation can be observed in tempering steels [16]. It is very important to focus on this aspect since, close to the edges of the ferritic sheets used for heating, a steep temperature gradient prevails in the austenitic TWIP steel, leading to the presence of temperatures ranging from ambient temperature up to the temperature of the ferritic sheet. Of course, different mechanisms are well known to lead to deterioration of properties of TWIP steels, for example, hydrogen-related effects such as delayed cracking [28,29]. In how far such mechanisms are active in the functionally graded TWIP steels will be characterized in future work. From Figure 5, it can be deduced that the degree of freedom for establishing the desired gradation in TWIP steel is tremendous. In the lower and upper part of the sample, two different temperatures (710°C and 690°C) were used for heat treatment and eventually the recrystallization effect here was less pronounced such that the decrease in hardness and increase in local strains were smaller than those in the middle section of the sample.

In summary, functionally graded TWIP steels with yet unachieved monotonic properties can be processed. Within a huge processing window, steep gradients can be achieved without suffering from issues present in other steels. Consequently, new design concepts featuring local adaptations of strength and ductility become feasible allowing for the production of light-weight parts of extraordinary performance.

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Note

1. Chemical composition in wt. %: 0.6 C, 22.36 Mn, 0.25 V, 0.2 Cr, 0.25 Si [17].

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