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Property optimization for TWIP steels – Effect of pre-deformation temperature on fatigue properties

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Abstract

The current work investigates the impact of pre-deformation temperatures on the microstructure evolution and the subsequent cyclic stress-strain response of high-manganese steel showing twinning-induced plasticity (TWIP) at room temperature (RT). Deformation at low temperatures increases the hardening rate at low to medium degrees of deformation through concurrent martensitic transformation. In contrast, high temperatures promote dislocation slip. Thus, employing pre-treatments at temperatures below and above RT leads to the evolution of considerably different microstructures. Low-cycle fatigue experiments revealed distinct differences for the pre-treated TWIP steels.

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Keywords: High-manganese steel, TWIP/TRIP, cryo-forming, fatigue, microstructure

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1. Introduction and Motivation

The performance of various high-manganese austenitic steels under monotonic and cyclic loading was investigated in many studies in recent years [1-5]. The reason for the intense interest in these steels is their superior performance under different loading conditions. In particular, the application of high-strength steels showing high ductility opens up new design possibilities in the automotive industry for crash-relevant parts as well as for light-weight construction [1]. Besides the chemical composition and the initial grain size, an important influence factor for the deformation mechanisms active is the deformation temperature. With a change of the temperature the stacking fault energy (SFE) is influenced, which in turn controls the dominant deformation mechanism [1-5]. Twinning, martensitic deformation and dislocation slip can occur simultaneously. However, twinning is favoured at SFE values between 20-25 mJ m^{-2}, whereas at lower SFE values the transformation-induced plasticity (TRIP) effect is more pronounced and at higher SFE values almost pure dislocation glide occurs [1-5]. In light of the envisaged applications, it can be assumed that pre-deformed components, i.e. parts formed by plastic deformation, will be employed under arbitrary loading regimes often including cyclic loads. Very recently, forming operations at cryogenic temperatures have been proposed in order to increase the monotonic performance, i.e. yield and ultimate strength. Thus, TWIP steels can directly be optimized through forming [6]. However, data on the behaviour of cryo-formed components under cyclic loading are not available in the open literature, yet. To gain deeper insight into the mechanical properties of a TWIP steel following pre-forming, the current study was undertaken with a focus on the low-cycle fatigue (LCF) regime.

2. Experimental

The high-manganese austenitic TWIP steel X40MnCrAl19-2 investigated in the current study was hot-rolled to 3 mm thick blanks by Hoesch-Hohenlimburg GmbH. The average grain size of 20 µm in the as-received condition was determined by means of electron microscopy. The material has a chemical composition of Mn – 19 wt.%, C – 0.4 wt.%, Cr – 2.2 wt.%, Al – 1.2 wt.%, Si – 0.3 wt.% and balance of Fe. For pre-straining at non-ambient temperatures (400 °C, 200 °C, -100 °C and -196 °C) a custom-built setup was used. Tensile pre-straining at different temperatures was conducted using dog-bone shaped samples with a length of 190 mm and a nominal gauge section of 80 mm × 17 mm × 3 mm. The different pre-deformation levels were realized using a screw-driven mechanical testing machine in displacement control at a displacement rate of 2 mm min^{-1}. Low temperatures were achieved employing a custom-built chamber filled with liquid nitrogen (LN_2) or chilled ethanol, respectively. The elevated temperatures were realized by means of hot-air flow, where the sample temperatures including temperature gradients were measured and controlled with a thermocouple and an infrared camera. Obviously, the type of deformation has a significant influence on martensite evolution and eventually mechanical properties. However, for the sake of clarity, only one pre-straining procedure was employed in the current work. For comparison to other forming operations, the reader is referred to [6]. Following the pre-treatments, small dog-bone shaped specimens with a nominal cross section of 1.5 mm × X[†] mm and 8 mm gauge length were cut by electro-discharge machining (EDM). The subsequent tensile and fatigue test were done in a servo-hydraulic load frame in displacement control (crosshead speed of 2 mm min^{-1}) and in strain control at a strain rate of 6×10^{-3} s^{-1}, respectively. Strains in the tensile tests were calculated from displacement data based on a reference test employing a miniature extensometer. The fatigue tests were done at room temperature with different strain amplitudes ranging from $\Delta\varepsilon/2 = 0.23$ % to $\Delta\varepsilon/2 = 0.6$ %. The samples were prepared for transmission electron microscopy (TEM) work by twin-jet polishing employing a perchlorid acid solution.

[†] X corresponds to the residual sheet thickness after the different pre-deformation treatments of samples prepared from sheet material with an initial thickness of 3.0 mm. Based on previous work on miniature specimens, the effect of the current thickness variations is negligible, such that comparison of data is reasonable.

3. Results and Discussion

3.1. Mechanical properties following pre-deformation

The results of the tensile tests at RT following pre-deformation under different conditions are shown in Figure 1. As compared to the X40MnCrAl19-2 in its as-received condition the yield strength as well as the ultimate tensile strength are increased for all pre-treated samples. Expectedly, strain to failure is decreased concomitantly. The curves shown in Figure 1 seem to be arranged in three distinct groups. Highest stresses are seen for the steels pre-strained to highest degrees at RT and below. However, these conditions show an unfavourable post yielding behaviour as no hardening is observed. Following pre-deformation at temperatures above RT, the increase in strength is only moderate. Still, the material strained to 45 % at 200 °C is able to meet the strength of the cold deformed conditions, i.e. the conditions following 20 % of deformation at cryogenic temperatures depicted in blue. The TWIP steel pre-deformed to medium strains at low temperatures is characterized by well-balanced properties, i.e. high yield strength, post-yield hardening and high remaining ductility. Thus, cryo-forming is a very attractive method for obtaining high-strength components made from TWIP steel even at low degrees of deformation.

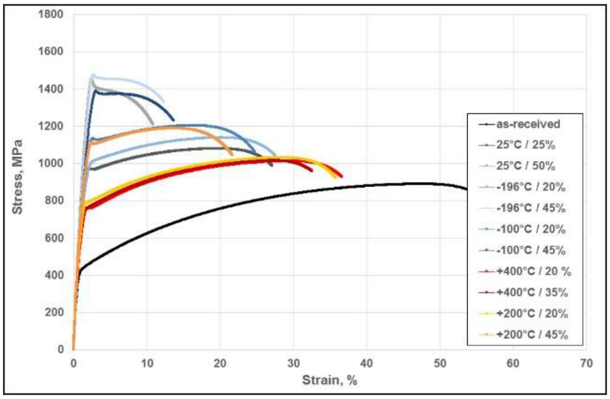

Fig. 1. Monotonic stress-strain curves of the X40MnCrAl19-2 steel following different pre-treatments (partly recompiled from [6]).

3.2. Microstructure evolution

Figure 2 shows the microstructures of the X40MnCrAl19-2 TWIP steel in different conditions. The as-received condition (Fig. 2a) contains only a few dislocations. In addition, recrystallization twins are visible on different length scales (not shown). After deformation to an elongation of 50 % at RT the microstructure is heavily deformed. Numerous twins, stacking faults and a high density of dislocations are visible in the deformed microstructure as can be in part deduced from Fig. 2b. The samples deformed at -196 °C to an elongation of 40 % show, in addition to twinning, fractions of ε-martensite (not shown) as well as α′-martensite (Fig. 2c). A more detailed analysis of microstructure evolution is currently in progress and will be published elsewhere. Following deformation at 400 °C martensitic transformation and twinning cannot be seen (Fig. 2d). TEM images following fatigue (not shown) revealed that in the pre-strained samples changes can hardly be seen. Generally, dislocations tend to form cell structures [5], which is most pronounced for the samples pre-strained at elevated temperatures.

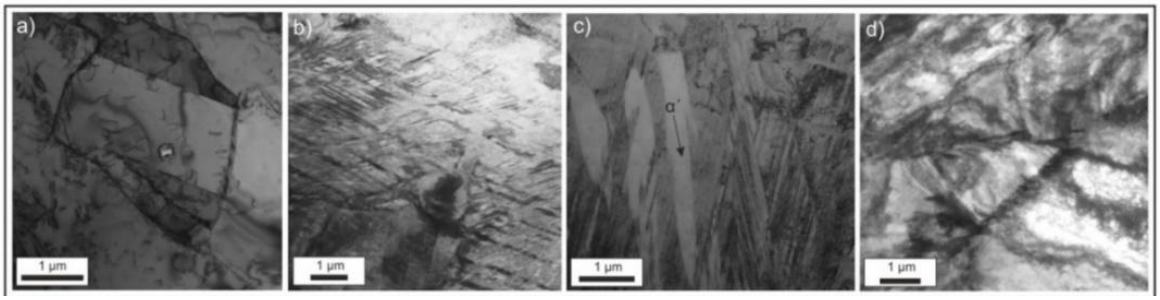

Fig. 2. TEM bright field images of a) the as-received X40MnCrAl19-2 and after deformation to b) 50 % at RT, c) 45 % at -196 °C and d) 35 % at 400 °C.

3.3. Fatigue behaviour under LCF loading

A set of curves depicting the cyclic stress response of different pre-treated samples is shown in Figure 3. Due to inferior monotonic properties (Fig. 1), samples pre-treated at elevated temperatures were not considered. Following hardening within the initial 100 cycles, the as-received material shows cyclic softening independent of the applied strain amplitude. This is induced by rearrangement of dislocations as already detailed in [5]. By contrast, the pre-strained samples show cyclic stability or even subtle cyclic hardening (Fig. 3b), at least at the low to medium strain amplitudes (up to a strain amplitude of 0.4 %), i.e. for plastic strain amplitudes far below 0.1 %. Thus, twins, martensite and dislocations imposed by the pre-treatment lead to intense interactions in the microstructure. This in turn impedes dislocation rearrangement and, thus, cyclic softening.

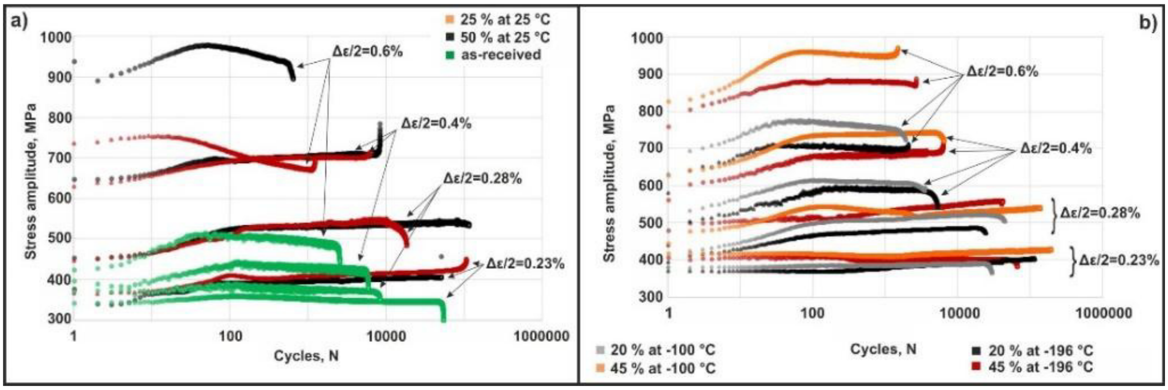

Fig. 3. Cyclic deformation response of pre-treated TWIP steel samples fatigued at different strain amplitudes. In a) the behaviour of the as-received ant the material treated at RT is shown, b) reveals the behaviour of the TWIP steel pre-deformed at low temperatures.

As intense cyclic hardening after initial increase of the stress amplitude, i.e. during the first 100 cycles, does not occur (Fig. 3), twinning or martensitic transformation induced by fatigue loading can be neglected as already found for other TWIP steels [5]. Finally, the build-up of mean stress has been found for all pre-treated conditions in accordance to [5]. In order to evaluate the LCF performance of all pre-strained conditions in more detail, the evolution of the stress amplitudes as well as the fatigue lives have been extracted from the fatigue data. Figure 4a shows the absolute value of the stress amplitude for a strain amplitude of 0.4 %. Maxima are found for either highest degrees of deformation at RT or medium degrees of deformation at cryogenic temperatures. With respect to fatigue lives at a strain amplitude of 0.28 % the same kinds of pre-treatments lead to the highest values (Fig. 4b).

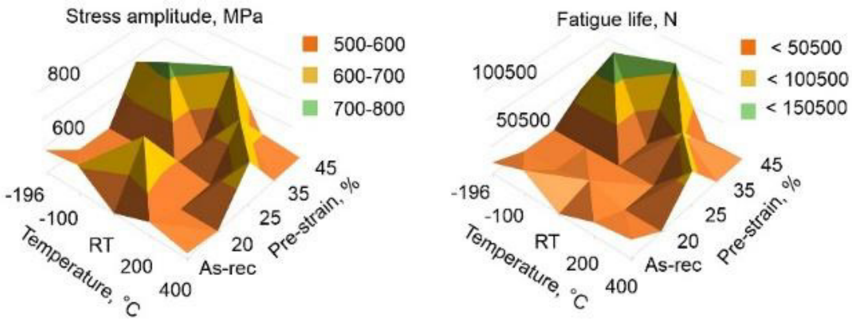

Fig. 4. Landscapes revealing the impact of pre-deformation parameters on a) the half-life stress amplitude at a strain amplitude of 0.4 % and b) the fatigue lives at a strain amplitude of 0.28 %.

4. Conclusions

- Low temperatures during deformation lead to high yield and ultimate tensile strength in TWIP steels. A balanced ratio of microstructural features needs to be attained for superior properties.
- Under strain controlled cyclic loading, the stress response is increased for pre-strained samples as compared to the as-received material. For low and medium strain levels, softening does not occur and fatigue lives are similar or increased. The optimum pre-straining procedure has to be chosen based on the actual fatigue loading spectrum to allow for significant fatigue life extension.

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