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Research Article

Effect of Deformation Temperature on Microstructure Evolution and Mechanical Properties of Low-Carbon High-Mn Steel

Adam Grajcar, Aleksandra Kozłowska, Santina Topolska, and Mateusz Morawiec

Institute of Engineering Materials and Biomaterials, Silesian University of Technology, 18a Konarskiego Street, 44-100 Gliwice, Poland

Correspondence should be addressed to Adam Grajcar; adam.grajcar@polsl.pl

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This work addresses the influence of deformation temperature in a range from −40°C to 200°C on the microstructure evolution and mechanical properties of a low-carbon high-manganese austenitic steel. The temperature range was chosen to cope at the time during sheet processing or car crash events. Experimental results show that yield stress and ultimate tensile strength gradually deteriorate with an increase in the tensile testing temperature. The dominant mechanism responsible for the strain hardening of steel changes as a function of deformation temperature, which is related to stacking fault energy (SFE) changes. When the deformation temperature rises, twinning decreases while a role of dislocation slip increases.

1. Introduction

Among new steel grades developed for application to car bodies [1–5], high-manganese austenitic steels are attractive materials for the automotive industry because of their unique combination of high strength, ductility, and formability. High-manganese steels are characterized by a high work-hardening rate resulting from TRIP (transformation-induced plasticity), TWIP (twinning-induced plasticity), or SIP (shear-induced plasticity) effects [6, 7]. A lot of reports concerning the mechanical behavior of high-Mn TRIP or TWIP steels have already been available in the literature. Most of them characterize the influence of heat treatment parameters on microstructure, mechanical properties [8–11], and corrosion behavior of the steels [12, 13].

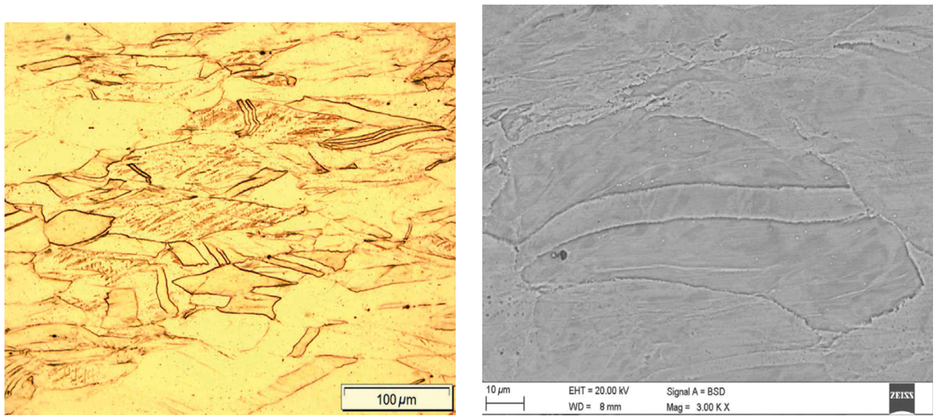
The dominant mechanism of strengthening occurring in these steels strongly depends on the chemical composition, particularly on carbon, manganese, aluminum, and silicon contents. The deformation mechanism depends also on stacking fault energy, strain rate, and temperature. TRIP effect is dominant when SFE is lower than 25 mJ/m^2—some fraction of austenite transforms into ε or α' martensites. When SFE value is in a range of 25–60 mJ/m^2, deformation twins occur (TWIP effect). If SFE value is higher than 60 mJ/m^2, the steel is strengthened mostly by work hardening. Aluminum strongly increases SFE, whereas silicon causes an opposite effect [14–16].

Deformation temperature changes affect significantly the SFE, which in turn influences the character of the hardening. Shterner et al. reported [17] that the increase of deformation temperature of the Fe-0.6C-18Mn-1Al TWIP steel caused a decrease of yield strength, ultimate tensile strength, and total and uniform elongation. The highest mechanical properties of the TWIP steel were detected at room temperature. They decrease gradually with the increase in deformation temperature. They also reported [17] that the work-hardening behavior was attributed to complex dynamic strain-induced microstructural changes including dynamic recovery, dislocation dissociation, stacking fault formation, mechanical twinning, and dynamic strain aging.

Asghari et al. [18] classified the strengthening mechanisms depending on the characteristic temperature regimes in unidirectional compression tests: 25–300°C, 300–700°C, and 700–1000°C. The Fe-0.07C-18Mn-2Si-2Al steel showed transformation-induced plasticity effect (TRIP effect) as the major deformation mechanism from 25°C to 200°C, whereas deformation twinning (TWIP effect) started from 200°C to 300°C. Above 700°C the dynamic restorations, recovery and

Table 1: Chemical composition of the investigated steel (wt.%).

C	Mn	Si	Al	S	P	Nb	Ti	N	O
0.065	26.00	3.08	2.87	0.013	0.002	0.034	0.010	0.0028	0.0006



(a) (b)

Figure 1: Optical micrograph (a) and SEM image (b) of the X6MnSiAlNbTi26-3-3 steel before tensile test.

recrystallization play a key role in microstructural evolution of the experimental steel in accordance with the diminishing SFE. Similar results have been shown by Salas-Reyes et al. [19] for the Fe-0.1C-21Mn-2.5Si-1.6Al steel during compression tests in a temperature range of 25°C to 1000°C. The local composition of steel may be changed during hot deformation, for instance due to the strain-induced precipitation or decomposition, thereby resulting in SFE changes [19].

Eskandari et al. [20] studied the hot ductility behavior of the Fe-0.45C-22Mn-1.5Al-1.5Si steel in uniaxial hot tensile tests in the temperature range of 700–1100°C under a constant strain rate. They indicated that the peak stress decreases as the temperature increases, from 250 MPa at 700°C up to 30 MPa at 1100°C. The highest ductility was detected at the intermediate temperature range (800–900°C). It was caused by dynamic recrystallization.

So far, the mechanical behavior of low-carbon high-Mn steels in a temperature range of 20–200°C and below room temperature has been investigated rarely [18, 19]. Most publications concern the mechanical properties of high-carbon high-manganese steels at elevated temperatures: 700–1000°C, which simulate the hot-rolling conditions. Therefore, the aim of this paper is to determine the effect of deformation temperature on the microstructure evolution and mechanical properties of low-carbon high-manganese steel in a temperature range −40°C to 200°C that is chosen to cope at the time during sheet stamping or car crashes.

2. Experimental Procedure

2.1. Material. The chemical composition of the X6MnSiAlNbTi26-3-3 steel used is given in Table 1. Carbon and manganese are major austenite stabilizers, whereas silicon and aluminum were added for providing solid solution strengthening. Small amounts of Nb and Ti were added for precipitation strengthening and grain refinement. The chemical composition of steel significantly affects SFE, which is related to the strengthening mechanisms [14–16].

A steel ingot (25 kg) was prepared by vacuum melting. Then, it was hot-forged using a high-speed hydraulic press with forging pressure of 300 tons in a temperature range from 1200°C to 900°C. The flat bars after forging were hot-rolled to a thickness of 4.5 mm. The thermomechanical processing included hot rolling of the flat samples in 3 passes (at temperatures: 1050°C, 950°C, and 850°C) to a final thickness of ~2 mm obtained at the finishing rolling temperature of 850°C. The hot rolling was conducted using a reversible rolling mill at a circumferential speed of rollers of $0.65\ m\cdot s^{-1}$. A solution heat treatment at 900°C for 20 min was followed by a rapid water cooling to room temperature.

2.2. Tensile Tests. 2 mm thick tensile specimens were machined from the hot-rolled sheet along the rolling direction to investigate the effect of the deformation temperature on the microstructure evolution and mechanical properties. The tensile tests were performed at −40°C, 20°C, 80°C, 140°C, and 200°C at a strain rate of $5 \times 10^{-3}\ s^{-1}$ using an INSTRON 4505 universal testing machine.

2.3. Microstructure Characterization. The microstructural analysis was performed using Zeiss Axio Observer Z1m optical microscope. The microstructural details were revealed with a scanning electron microscope Zeiss SUPRA 25 operating at 20 kV. The specimens at the initial state and after tensile tests were mechanically ground with SiC paper up to 1500 grid, polished with Al_2O_3 and then etched using 5% nital to observe microstructures.

3. Results and Discussion

3.1. Microstructural Evolution. Microstructure of the X6MnSiAlNbTi26-3-3 steel in the initial state is shown in

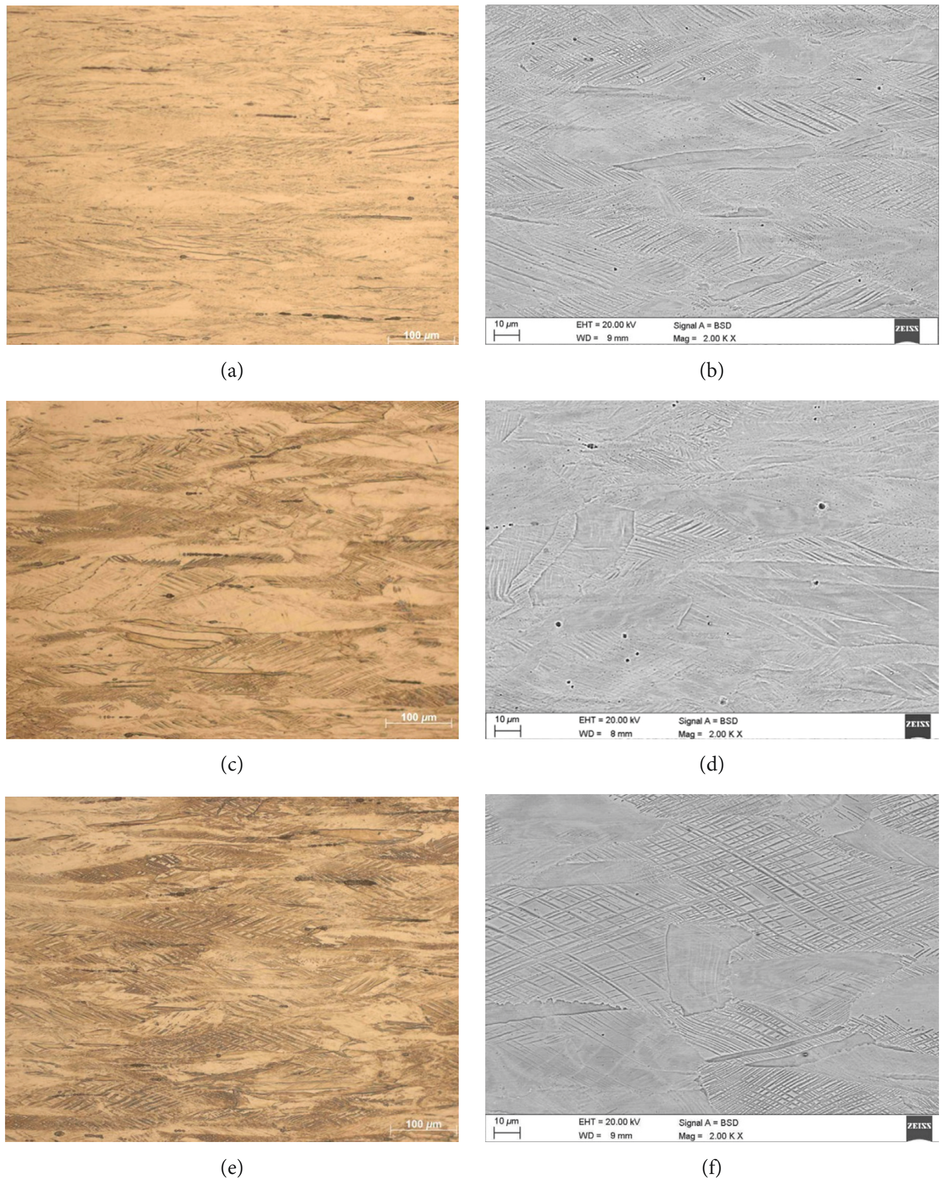


Figure 2: Microstructures of the X6MnSiAlNbTi26-3-3 steel deformed at a temperature of −40° ((a) LM; (b) SEM), 80°C ((c) LM; (d) SEM), and 200°C ((e) LM; (f) SEM) observed by a light microscope (LM), and a scanning electron microscope (SEM).

Figure 1. Austenite grains are relatively coarse and elongated along rolling direction. Annealing twins were also observed.

The results obtained from the tensile tests indicate a relationship among the test temperature, microstructure, and mechanical properties. The microstructure of the steel deformed in a static tensile test at −40°C is characterized by the presence of austenitic grains elongated according to the direction of applied tensile loading. With the reduction of deformation temperature the SFE decreases [18], therefore mechanical twinning occurred as a main strengthening mechanism (Figure 2(a)). The low SFE results in a reduction of stress levels necessary to initiate the twinning process. SEM image revealed also the presence of slip bands (Figure 2(b)). Shterner et al. reported [17] that, in the Fe-0.6C-18Mn-1Al steel, mechanical twins nucleated at the grain boundaries and then propagated across the grain interior, as the degree of deformation increased. Amount of deformation twins in the microstructure is related to the increasing dislocation density during deformation process. The microstructure of the steel deformed at room temperature is similar to the one obtained at −40°C. This concerns the amount of crossing slip lines and bands as wells as numerous deformation twins. The occurrence of the transformation-induced plasticity effect (TRIP) or twinning mechanism (TWIP) is common at relatively low test temperature. Shterner et al. [17] reported that, at a strain level of 0.4, the volume fraction of mechanical twins reduced from 11.2% at room temperature to 5% and 2.9% at 100°C and 200°C, respectively.

The microstructure of the sample deformed at 80°C indicates a dominant role of crossed slip lines and bands (Figures 2(c) and 2(d)). The amount of deformation twins is

Table 2: Mechanical properties of the tensile tested steel at each temperature.

Temperature (T)		Tensile strength (UTS) (MPa)	Yield stress ($YS_{0.2}$) (MPa)	$YS_{0.2}$/UTS	Total elongation (TE) (%)
1	−40°C	834	577	0.69	43.4
2	20°C	743	554	0.75	43.8
3	80°C	676	527	0.78	41.8
4	140°C	617	511	0.83	43.4
5	200°C	604	509	0.84	22.4

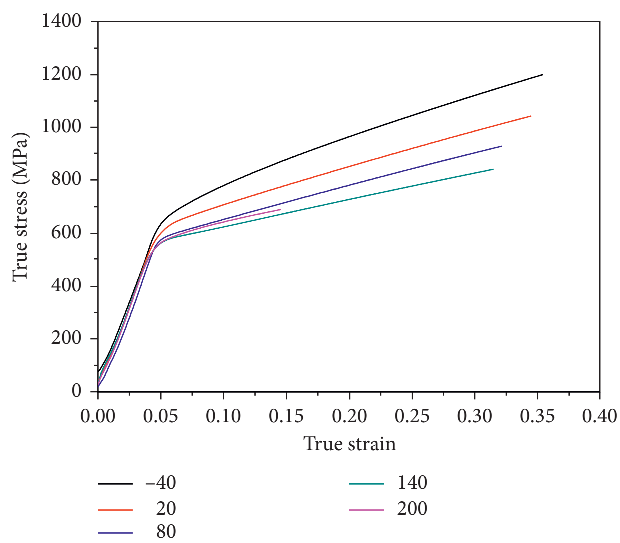


Figure 3: True stress-true strain curves in a uniform elongation range of the X6MnSiAlNbTi26-3-3 steel at various deformation temperatures.

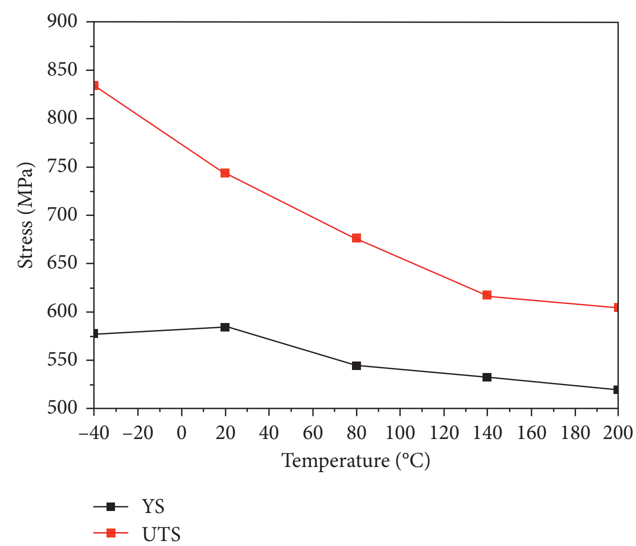


Figure 4: Mechanical properties of the X6MnSiAlNbTi26-3-3 steel: yield stress (YS) and ultimate tensile strength (UTS) at various tensile test temperatures.

smaller than in the samples deformed at −40°C and 20°C. Increasing the test temperature to 80°C results in an increase of SFE, which limits the twinning occurrence. The deformation of the sample at 140°C favors dislocation slip as a main deformation mechanism, while the formation of twins is strongly limited. The prevailing mechanism of deformation at 200°C appears to be dislocation slip (Figures 2(e) and 2(f)). Chen et al. [21] confirmed that deformation bands can be observed in pancaked austenite deformed in a non-recrystallization region, which bridge the grains by roughly parallel lines. No ε or α' martensites were observed in the temperature range −40°C to 200°C. Such behavior is typical for steels characterized by SFE > 20 mJ/m^2, resulting from the chemical composition.

3.2. Mechanical Properties. The mechanical properties of the steel tensile tested at each temperature is shown in Table 2, indicating a strong temperature dependence.

Figure 3 shows the true stress-true strain curves in the temperature range of −40°C to 200°C. The X6MnSiAlNbTi26-3-3 steel showed the best mechanical properties at −40°C, having a tensile strength (UTS) of 834 MPa, yield stress (YS) of 577 MPa, and total elongation of 43.4% (Figures 3–5). At −40°C, the dominant mechanism responsible for the high strain hardening of the steel is twinning (Figures 2(a) and 2(b)). The YS/UTS ratio in this case is 0.69, which indicates relatively high strengthening potential (Figure 5).

The steel deformed at 20°C is characterized by slightly lower mechanical properties (YS = 584 MPa; UTS = 743 MPa) than the one deformed at −40°C (Figure 4). The YS/UTS ratio rises to 0.75 (Figure 5). It shows the gradual lowering of strengthening intensity with the increase of deformation temperature. Total elongation remains at the same level ~43.8% (Figure 5). The combination of high strength and ductility both at −40°C and at room temperature is mostly related to twinning mechanism. At 80°C, the mechanical properties decreased: YS = 527 MPa and UTS = 676 MPa (Figure 4), which is related to a decrease in the density of deformation twins (Figures 2(c) and 2(d)) and a gradual increase of the SFE. The YS/UTS ratio increased to 0.78 (Figure 5). When the temperature increases, the role of slip lines and bands in the plastic deformation increases. However, the reduction of total elongation is relatively small (~2%) when compared to the specimen deformed at 20°C (Figure 5). Such a small reduction is due to the combination of mechanical twinning and slip and overall high plasticity of the austenite phase.

The specimen deformed at 140°C shows further lower strengthening effect than the samples deformed in a lower temperature range (Figure 3). YS and UTS are 511 MPa and 617 MPa, respectively. The YS/UTS ratio in this temperature

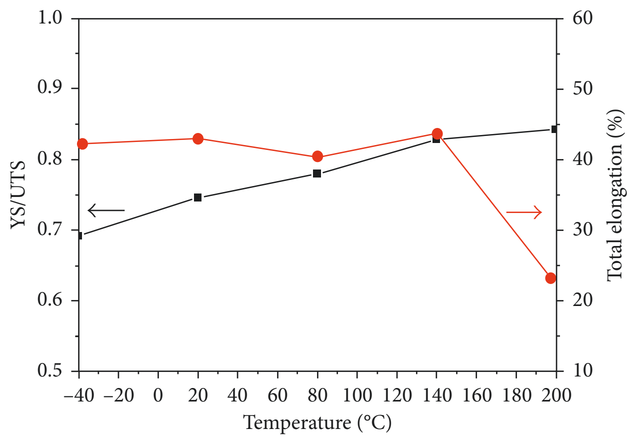


Figure 5: YS/UTS ratio (square) and total elongation (circle) of the X6MnSiAlNbTi26-3-3 steel at various tensile test temperatures.

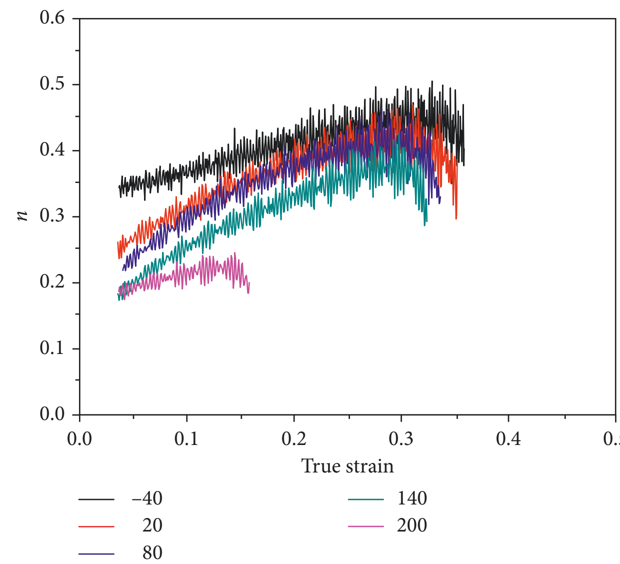


Figure 6: Work-hardening exponent n changes as a function of true strain at various tensile test temperatures.

corresponds to 0.83 (Figure 5). It indicates a significant decrease in the intensity of the strengthening. It is also reflected in a slope of the σ-ε curve (Figure 3). The temperature of 140°C favors dislocation slip as a main deformation mechanism. However, the change of dominant deformation mechanism from twinning to dislocation slip is not still too detrimental for total elongation (43.4%), but these conditions strongly affect the strength properties.

The mechanical properties determined for the sample deformed at 200°C are the lowest compared to the results obtained at the lower temperatures (Table 2). YS and UTS are 509 MPa and 604 MPa, respectively (Figure 4), and YS/UTS = 0.84 (Figure 5). The slight slope of the σ-ε curve shown in Figure 3 indicates the minimum intensity of the strengthening. The specimen deformed at 200°C is characterized by a rapid decrease of plasticity expressed as the lowest total elongation = 22.4% (Figure 5). The plasticity is almost twice lower when compared to the other samples. The significant decrease of plasticity is due to disappearance of mechanical twinning and increased importance of diffusion processes activated at elevated temperatures.

Asghari et al. [18] reported that the mechanical twinning occurring inside the austenite grains by the variation of deformation temperature strongly affects the mechanical behavior of steel. The mechanical twins subdivide the austenite grains and reduce the dislocations mean free path. Therefore, the twin boundaries act as strong barriers to dislocation motion. Hence, higher mechanical properties reflect the occurrence of mechanical twinning. Mechanical twins were observed in the microstructures of samples deformed in the temperature range: −40°C–80°C (Figures 2(a)–2(d)). Eskandari et al. [20] observed mechanical twins in a temperature range 150°C–600°C during compression of the Fe-0.1C-21Mn-2.5Si-1.6Al-0.02Nb-0.02Ti-0.01V steel. Shterner et al. [17] showed that mechanical properties such as YS and UTS of the Fe-0.6C-18Mn-1A steel decreased with increasing temperature of tensile test: from YS = 500 MPa and UTS = 1000 MPa at room temperature to YS = 430 MPa and UTS = 840 MPa at 200°C. Total elongation was high between 20°C and 100°C (60–65%) and gradually decreased above 100°C (e.g., 47% at 200°C).

The steel shows the TWIP effect most intensively at −40°C. The mechanical twins were detected up to ~80°C. Asghari et al. [18] and Eskandari et al. [20] observed the TWIP effect in a temperature range 200–300°C. It seems that the steel shows an optimal TWIP effect at lower temperatures. In order to obtain a better TWIP effect at room temperature and at increased temperatures, some modification of the chemical composition of the steel would be required. It is expected that TWIP effect could be enhanced by reducing the aluminum and manganese contents, when the SFE at room temperature would be high.

The mechanical twinning is believed to significantly influence the work hardening of high-Mn steels. Presence of mechanical twins in the microstructure blocks the movement of dislocation glide [17, 21]. The gradual increase in the amount of mechanical twins and the increase of deformation level prevent the localization of deformation. The work-hardening exponent n gradually rises as the degree of deformation increases (Figure 6). The highest value of n exponent = 0.46 was obtained at −40°C (Figure 7). It is related to the dominant character of twinning mechanism, which decreases with increasing the deformation temperature. With increasing test temperature, the strengthening potential expressed as n values gradually decreases. Shterner et al. [17] suggested that the interactions of glide dislocations with stacking faults have greater contributions to the work-hardening behavior (plateau region) compared with the mechanical twinning at room temperature. The present steel has a relatively small grain size (high grain boundary area), which significantly enhances the interactions between the dislocations and the grain boundaries. However, at 200°C grain boundaries start to lose their reinforcing character due to the initiation of diffusion processes.

The deformation temperature strongly affects the work-hardening rate (Figure 8). The shape of the curves is typical; that is, the dσ/dε values decrease rapidly at an initial range of

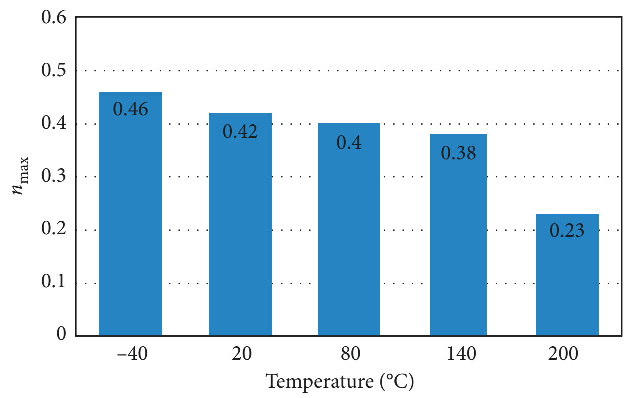


FIGURE 7: Maximum values of work-hardening exponent n_{max} at various tensile test temperatures.

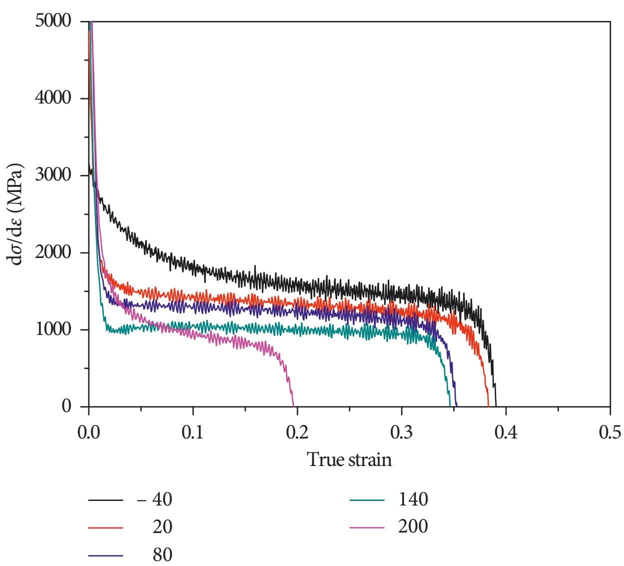


FIGURE 8: Work-hardening rate as a function of true strain at different tensile test temperatures.

deformation. Then, the work-hardening rate stabilizes at a constant level for the samples deformed between −40°C and 140°C due to the combined occurrence of deformation twinning and deformation slip. A various level of the deformation twinning at various temperatures is reflected in a different constant value of $d\sigma/d\varepsilon$. It is circa 1900–1800 MPa for the temperature of −40°C and about 1000 MPa for a sample deformed at 140°C. The different behavior is registered for a sample deformed at the highest deformation temperature, where a continuous decrease of the work-hardening rate can be observed due to a lack of deformation twinning.

4. Conclusions

The present study investigated the effect of deformation temperature on the microstructure evolution and mechanical properties of low-carbon high-Mn steel. The steel showed the best mechanical properties at −40°C due to the TWIP effect. Yield stress and ultimate tensile strength gradually deteriorated with an increase in the deformation temperature from −40°C to 200°C. The reduction of the mechanical properties was related to the decrease in the contribution of twinning, whereas that of dislocation slip increased. The significant reduction of the plasticity occurred at 200°C due to a lack of mechanical twinning, and diffusion processes activated at elevated temperatures.

The friction occurring during steel sheet forming or a crash event can lead very often to an increase in the temperature of a formed metal piece to ~100°C. To maximize the potential application of the high-Mn steel, its chemical composition should be modified to reduce its SFE in a desired temperature range from 20°C to 100°C. As a result, the optimum window of mechanical properties would shift to higher temperatures. One of the options is to reduce the aluminum content.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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