The Effect of Deformation Temperature on the Mechanical Properties and Microstructural Evolutions of High Manganese TWIP Steel

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Abstract

In this study, the effect of tensile test temperature (148 to 673 K) on the microstructural evolutions and the mechanical properties of high manganese twinning induced plasticity (TWIP) steel with the chemical composition of Fe-31Mn-3Al-3Si (wt. %) was investigated. XRD, SEM and TEM were used to study the microstructural evolutions. Stacking fault energy (SFE) of the alloy was also calculated by a thermodynamic model. The results indicated that yield strength and tensile strength of steel were gradually decreased with increasing the temperature. However, total elongation reached a maximum value with increasing the temperature up to 248 K. Furthermore, microstructural investigations showed that in the temperature range of 473 to 673 K (SFE: 60-85mJ/m^2), deformation was mainly controlled by dislocation gild and there was no evidence suggesting that twins were formed during deformation. In the temperature range of 248 to 473 K (SFE: 35-60mJ/m^2), both mechanisms contributed to reacing a maximum ductility. In the temperature range of 248 to 148 K (SFE: 20-35mJ/m^2), twinning and dislocation glide were still the dominant deformation mechanisms, but the change in the formation kinetic of twins probably led to decrease in the total elongation.

Keywords: TWIP steel; Deformation temperature; Stacking fault energy

1. Introduction

Over the past decade, high manganese austenitic steels containing 15-30% Mn and other alloying elements such as Al, Si and C have attracted great attention, especially in the automobile industry. Martensitic transformation and mechanical twinning as well as dislocation gliding occur during the deformation of these steels. These microstructural evolutions enhance the work hardening rate, leading to the excellent combination of strength and ductility 1-4).

It is well-known that the main deformation mechanism depends on the stacking fault energy (SFE) of an alloy system. On the other hand, SFE is related to the chemical composition and temperature 5).

The effect of alloying elements such as Mn, Si, Al and C on the SFE of high manganese steels shows that if the SFE is between 20-60mJ/m^2, twinning occurs considerably. If the SFE is more than this range, dislocation glide is the sole mechanism causing deformation. However, on the condition that the SFE is lower than about 20mJ/m^2, phase transformation is the predominant deformation mechanism 5-9).High manganese austenitic steels are a good candidate for automobile industry as structural materials. Also, other properties of these steels such as structural stability, non-magnetic property and excellent ductility/toughness make them suitable for cryogenic applications 10-11).

From the literature 12-14), it can be understood that the effect of deformation temperature on the mechanical properties of twinning induced plasticity (TWIP) high Mn-steels has been investigated.

For example, Shterner et al. 12) conducted some tensile tests in the range of ambient temperature to one of 673 K (400 °C) to study the active deformation mechanism in Fe-18Mn-1.5Al-0.6C (wt. %) TWIP steel. They found that mechanical twinning was the dominant mechanism at low temperatures beside the dynamic strain aging (DSA) that resulted from the high carbon content. At a temperature higher than 573 K (300 °C), mechanical twins were hardly observed in the microstructures, even at fracture strains.

Chen et al. 13) performed tensile deformation experiments on Fe-23Mn-2Al-0.2C (wt. %) TWIP steels at a relatively wide temperature range from 213 to 873 K (-60 to 600 °C) and their peak values for the mechanical properties appeared at 573 K (300 °C) during high temperature deformation. Also, Dobrzański et al.14) studied the hot deformation behavior of different carbon contained TWIP steels

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in continuous and multi-stage compression tests performed in a temperature range of 1123 to 1373 K (850 to 1100 °C) using the Gleeble thermomechanical simulator.

In this work, in order to demonstrate the effect of a relatively wide range of deformation temperatures on the microstructural evolutions and the mechanical properties of such high manganese austenitic steels, carbon free 31Mn-3Al-3Si (wt. %) standard TWIP steel was investigated in a temperature range of 148 to 673 K (-125 to 400 °C) with a high accuracy of temperature measurement.

2. Materials and Procedures

Cold rolled (90% reduction) TWIP steel sheets with the thickness of 1mm and the chemical composition of Fe-31Mn-3Al-3Si (in wt %) and very small amounts of carbon (~50 ppm) were used in this study. In order to obtain a fully recrystallized structure, the as-received sheet was annealed at 850°C for 120 min. Metallographic examinations showed that the grain size was around 72µm.

Fig. 1a shows the dimensions of tensile specimens. The rolling direction (RD), normal direction (ND), and transverse direction (TD) are denoted in Fig. 1a. All tensile tests were carried out with a strain rate of $10^{-3}s^{-1}$. Liquid nitrogen spray was used to obtain the low temperatures (Fig. 1b). In order to obtain a homogenous condition, all tensile specimens were kept at least for 10 min at each temperature. Controlling the temperature control and checking the accuracy of temperature measurement (±5 K) were done by a controller device equipped with the tensile test tank.

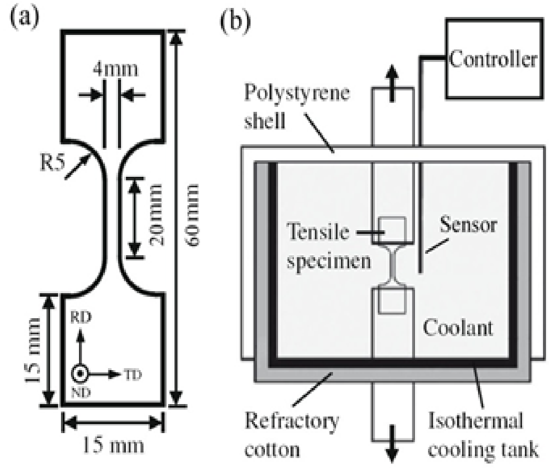

Fig. 1. Schematic illustration of a) the tensile specimen dimension and b) the set-up of low temperature tensile test tank.

High temperature tests were also carried out in another tensile test machine equipped with a small electrical furnace (an accuracy of ±1 K). Mechanical properties such as yield stress (YS), tensile stress (UTS), uniform elongation (UEL) and total elongation (TEL) were obtained according to Ref. [15]. The XRD measurements were conducted between 40 and 100° at room temperature using a diffractometer (Shimadzu XRD-6000) with a Cu target and a step size of 0.05°.

The microstructures for SEM were revealed with 4% nital. SEM observations were conducted on a JEOL JSM-5500 scanning electron microscope operating at 15 kV. The thin foils, which were perpendicular to TD, were prepared for TEM by twin-jet electro polishing in a 10% $HClO_4$+90% CH3COOH solution, and observed with a JEOL 3010 TEM operating at a nominal voltage of 300 kV. In addition, the SFE was calculated by using a thermodynamic model proposed by Grassel et. al [16] in the investigated temperature range. The details of this model are given in the appendix of Ref [17].

3. Results and Discussion

In Fig. 2a, the effect of tensile test temperature on engineering stress-engineering strain curves of all samples is shown. For further investigations, the quantitative data obtained from these curves, such as YS, UTS, UEL and TEL, as well as the calculated values of SFE is given in Fig. 2b. As can be seen, YS and UTS were decreased gradually with increasing the temperature. This behavior is generally seen in FCC metals and alloys. However, TEL reached to the maximum of 96% with increasing the temperature from 148 to 248 K and then decreased when temperature was increased to the higher values. The same behavior was observed for UEL as can be seen in Fig. 2b.

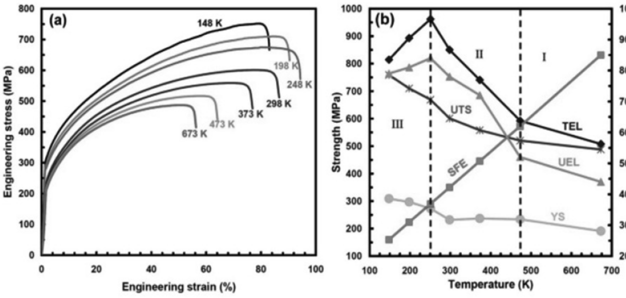

Fig. 2. The effect of tensile test temperature on a) engineering stress-engineering strain curves and b) mechanical properties and SFE

By taking into account the results of XRD (Fig. 3) and the calculated values of SFE, Fig. 2b can be subdivided into three regimes. It must be noted that the phase composition of all tensile samples after fracture was the same as that before the tensile test. In other words, structures remained fully austenitic with some annealing twins and no phase transformations occurred during deformation in the investigated temperature range.

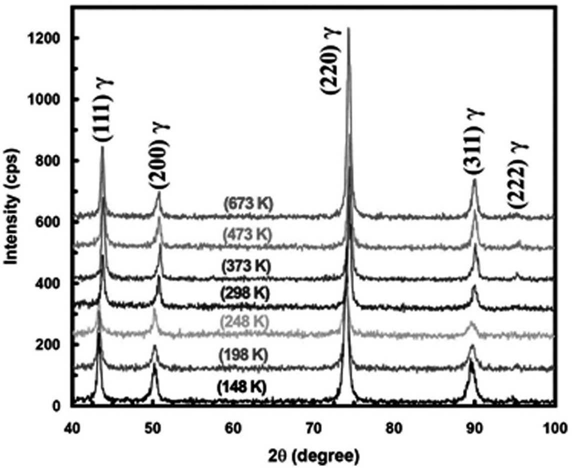

Fig. 3. XRD patterns of all strained samples at different tensile test temperatures after fracture.

In the temperature regime I (473 to 673 K), no phase transformation was detected by XRD and also, the SEM observations of fractured samples showed that there was no mechanical twin in the deformed structures (e.g. see Fig. 4a). Therefore, it could be concluded that the dislocation glide was the main deformation mechanism in this temperature range.

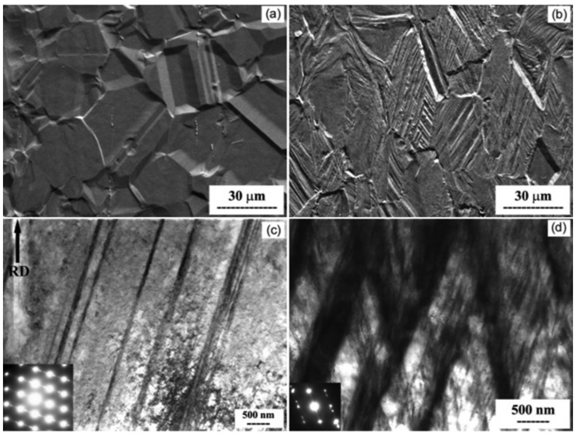

Fig. 4. SEM and TEM photographs of some strained samples after fracture at the test temperature of a) 673 K, b and c) 298 K and d) 148 K.

In the temperature regime II (473 to 248 K), SEM and TEM observations (e.g. see Fig. 4b and Fig. 4c) indicated that twinning occurred during deformation in this temperature range and the twin content was increased with decreasing the temperature. SEM micrograph (Fig. 4b) also showed that the main microstructural features were the formation of different mechanical twin configurations with the occurrence of secondary mechanical twin system in some grains intersected by the primary mechanical twins. Additionally, at the fracture point, most grains were elongated to the tensile direction. Elongation reached to a maximum value at 248 K, where the maximum twinning occurred in the deformed structure. Therefore, the increase in elongation with decreasing the temperature could be attributed to TWIP effect. Again, no phase transformation occurred in this temperature range.

In the temperature regime III (248 to 148 K), XRD revealed that no phase transformation occurred, but the TEL and UEL were decreased with decreasing the temperature. Also, mechanical twins were formed considerably in the deformed microstructures (e.g. see Fig. 4d). Some authors [3, 10)] believe that the change in the formation kinetic of twin is the reason for the reduction in ductility. In other words, with lowering the temperature, the twin formation is completed in an early stage of deformation, thereby resulting in lower elongation. So, it can be concluded that a gradual occurrence of twins is necessary to enhance ductility.

As mentioned in the introduction section, the SFE and its dependence on other parameters such as temperature principally can be regarded as an important factor to show the effect of temperature on the occurrence of the main deformation mechanism in TWIP steels. So, in this study, this relationship was considered as follows.

In the regime I, where the SFE was between 60 to 85mJ/m^2, deformation was mainly controlled by dislocation glide and no mechanical twins were observed in the deformed microstructures.

In the regime II, where the SFE was between 35 to 60mJ/m^2, both mechanisms (dislocation glide and twinning) contributed to the deformation process. In this range, the TEL reached the maximum value, where the SFE was about 35mJ/m^2 and temperature was 248 K. In fact, in this temperature, SFE value reached the optimal value and the enhancement of the TWIP effect in these conditions led to higher ductility.

In the regime III, where the SFE was between 20 to 35mJ/m^2, twinning and dislocation glide were still the dominant mechanisms. However, the change in the formation kinetic of twinning probably led to the decrease in ductility.

Although, in the studied temperature range, no evidence showing phase transformation was found in the TEM and XRD investigations, it seemed that by further decreasing temperature, the occurrence of transformation induced plasticity (TRIP effect) was more probable.

4. Conclusion

The study of the effect of tensile test temperature in the range 148 to 673 K on the mechanical properties and microstructural evolutions of Fe-31Mn-3Al-3Si TWIP steel showed that the TWIP effect could be enhanced by the change in the deformation temperature.

This enhancement happened when the SFE reached the optimal value at 248 K. Additionally, in the investigated temperature range, the studied TWIP steel remained stable (austenitic) and non-magnetic; also the excellent combination of strength/ductility could be obtained. Therefore, it can be concluded that this steel with essential parameters for developing cryogenic alloys can be used in the cryogenic applications as well as relatively high temperature ones.

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