Effect of Deformation Temperature on the Mechanical Behavior of a New TRIP/TWIP Steel Containing 21% Manganese

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Abstract
In recent years, TRIP/TWIP steels have been the focus of great attention thanks due to their excellent tensile strength-ductility combination. The compression tests were performed at different temperatures from 25 to 1000°C to study the mechanical behavior of advanced austenitic steel with 21% manganese plus bearing Ti. The results indicated that the plastic deformation is controlled by deformation-induced martensite and mechanical twinning from 25 to 100°C. However, at temperatures 200 to 1000°C the deformation twinning was merely observed. The occurrence of mechanical twinning at such high temperatures is a first-time observation in high manganese austenitic steels. Such mechanical twins led to grain refinement via grain partitioning.

Keywords: Metals and alloys, Phase transformation, Microstructure.

1. Introduction

In the past decade, new groups of low stacking fault energy (SFE) alloys such as transformation induced plasticity (TRIP) steels and twinning induced plasticity (TWIP) ones have been paid much attention due to a good combination of high strength and ductility [1)]. For example, it has been reported that a Fe-25Mn-3Si-3Al TWIP steel exhibited a relatively low flow stress of $R_{P0.2}$ =280 MPa, a moderate tensile strength of 650 MPa, and the extremely high elongation to failure of ε_f=95% [2)]. The mechanical properties of TRIP/TWIP steels have been described in detail elsewhere [2,3)]. As well established, the alloy would mainly reveal TRIP effect where manganese content is lower than 20%; while TWIP effect would be dominant where manganese content is higher than 25%. Therefore TRIP-TWIP steels should contain 15–25mass% Mn along with silicon and aluminum about 2–4mass% [4)]. These new high manganese steels lead to reduce the weight, save energy as well as energy absorption capacity in lightweight components [5)]. The TRIP and TWIP effects may individually result in an increase of the tensile strength and/or the uniform elongation of the material [6)]. Thus, the coexistence of TRIP and TWIP effects would lead to an outstanding increase of strength and ductility simultaneously.

The present authors' earlier works [7-11)], have conducted many studies on TRIP effects on the grain refinement of steels and their mechanical properties. A few studies have been recently performed on TWIP-TRIP steels [2,6,12-14)]. In the most latter steels, TRIP effect has been activated at low enough temperature below 0°C; while TWIP effect is effective at higher temperature up to 300-400°C. In the view of industrial requirements, the fabrication of TRIP-TWIP steel where TRIP effect acts at around the room temperature or even higher temperature in coexistence with TWIP effect, would be highly desired.

It is worth mentioning that boosting the high temperature strength of such steels can be achieved through high temperature mechanical twin formation. Twin boundaries are known as slip obstacles leading to similar effect of grain refinement [15)] via grain partitioning. The mechanical twinning has been observed at relatively low temperature in TWIP steels and there is no reporting on high temperature mechanical twinning. It should be emphasized that there is only one report on the formation of high temperature mechanical twinning in Ti–6Al–4V at 800°C and moderate strain rates during ECAE processing [15)].

To the best of the present authors' knowledge, no study has been reported about significant mechanical twinning activity during deformation at such high temperature under low to moderate strain rates in TRIP-TWIP steels. The present work reports the occurrence of TRIP effect at higher temperatures in coexistence with TWIP effects. In addition the mechanism of plastic deformation up to 1000°C has been investigated. Accordingly, the probable mechanisms at observed high temperature deformation twinning have been discussed.

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2. Experimental procedure

The cast ingots of steel were prepared using an induction furnace with chemical composition of Fe - 0.11C -21Mn-2.70 Si -1.60Al-0.01Nb-0.01Ti (in wt.%). The ingot was first homogenized at 1180˚C for 8h. Grain size was decreased to 40±5 µm by 5 passes hot rolling at the temperature range of 1000–1200˚C with the total strain of 1.3 and the strain rate of 5 s^{-1} followed by water quenching. The stress–strain response of the steel has been studied through hot compression testing scheme from 25 to 1000°C at constant strain rate of 0.01 s^{-1} using a Gotech AI-7000 universal testing machine. The compression tests have been conducted according to ASTM E209 standard. In order to investigate the occurrence of either TRIP or TWIP effects, Ferriteoscope MP30 (calculate magnetic phase) and conventional metallography have been utilized. The microstructures have been examined using an optical microscope and scanning electron microscopy, equipped with an electron backscatter diffraction (EBSD) operating at 20 kV after electro-etching in 65% nitric acid solution. Moreover, the actual martensite content was determined by the following equation [9]:

Vol. % martensite = 1.75 × Ferriteoscope reading

3. Results and discussion

The Ferriteoscope testing shows that the as-cast microstructure is consisted of 99.5% austenite & delta ferrite. The as-homogenized material held a coarse grain size of 600±100 µm including annealing twins. Figure 1 shows the true stress–true strain variation of hot-rolled specimens with temperature (in the range of 25 to 1000˚C). As seen, the experimental TRIP-TWIP steel exhibits high compressive strength 1180±10 MPa with the yield strength of 375±5 MPa after straining to 0.6 at 25˚C. However, strength level varies with deformation temperature and this may be categorized through three temperature ranges: 25 to 100˚C, 100 to 200˚C and 200 to 1000˚C.

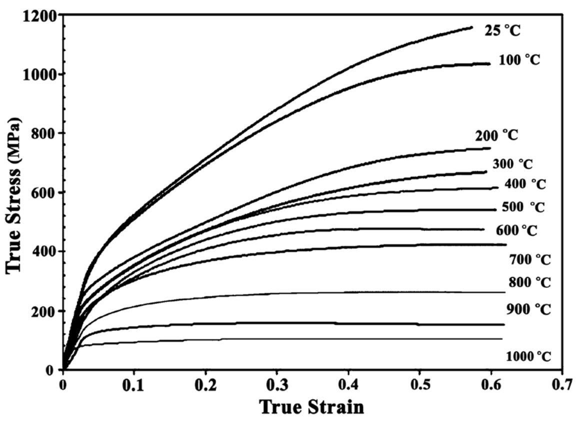

Fig. 1. The effect of hot compression on true stress–true strain response of the hot-rolled specimen.

The significant variation of strength (in the temperature range of 100 to 200˚C) is attributed to the change of deformation mechanism from TRIP-TWIP to merely TWIP effect during straining. This is clearly indicated in Figure 2 by which the relationship between the volume fraction of martensite and deformation temperature is demonstrated. As seen, the volume fraction of deformation-induced martensite reaches to 60% and 18% after straining to 0.6 (true strain) at 25˚C and 100˚C, respectively. Also, there is no martensite in all deformed specimens at 200˚C to 1000˚C. These results indicate that deformation mechanism has been altered during compression at 100˚C to 200˚C. The exact temperature of changing deformation mechanism need to more study during compression between 100 to 200˚C. The microstructure observation showed that the mechanical twinning has been detected in deformed specimens at all temperatures while the martensite plates have been exclusively recognized up to 100˚C.

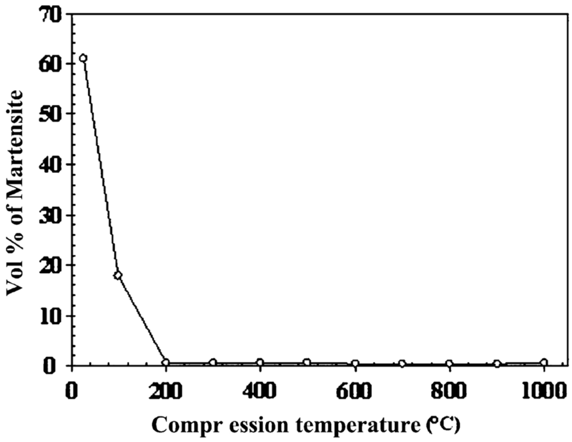

Fig. 2. The effects of compression temperature on deformation-induced martensite formation.

Figure 3 displays the microstructures of mechanical twinning after compression at 800 and 1000˚C (0.6, true strain). As seen, the grain has been partitioned by the twins. Such twins have been also observed in as-homogenized specimens after hot compression at 800˚C and 900˚C (Figure 4).

Although it is the first time that the occurrence of mechanical twinning at such high temperature in TRIP-TWIP steel is suggested, G. Yapici et al. [15] have already demonstrated the occurrence of mechanical twinning at 800˚C in Ti alloy during ECAE. This was attributed to the severe state of plastic deformation (i.e., high stress, strain and strain rate) imposed during ECAE process, along with the favorable texture evolved during deformation. In the present work, however, the twinning has occurred under hot compression at lower stress level than that of ECAE process.

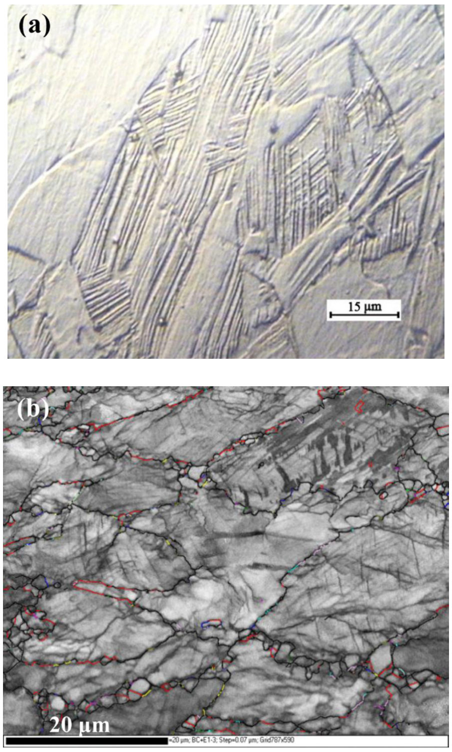

Fig. 3. The microstructure of hot-rolled specimen after straining to 0.6 at 800°C: (a) optical micrograph and (b) SEM-EBSD (band contrast) micrograph.

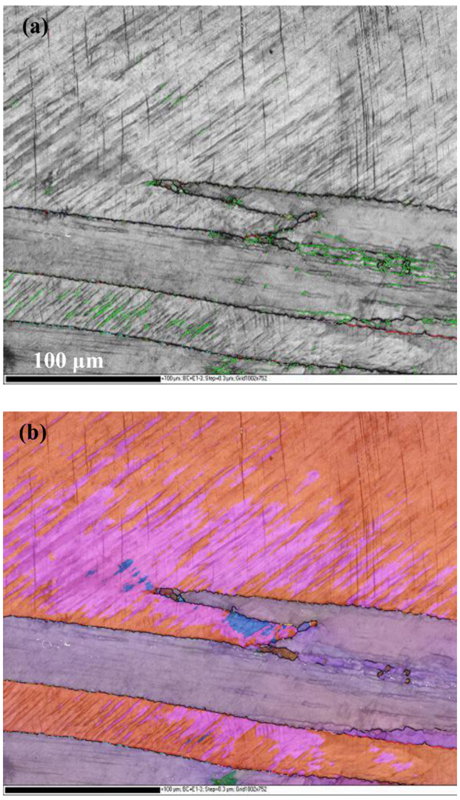

Fig. 4. SEM-EBSD micrographs of the homogenized materials after hot compression at 900°C to 0.6 true strain under strain rate of 0.01 s^{-1}: (a) band contrast image and (b) color map. The green lines represent the moderate misoriented deformation twin with angle of 15°.

The mechanical twinning was also observed in Ti single crystals [16] above 400°C under compression loading. This was attributed to the fact that, while the critical shear stress for the nucleation of a definite mode of twin formation increases with increasing temperature, another mode of twin formation decreases with increasing temperature. It is believed that [16,17] as the required stress level increases, the separation distance between twinning partial dislocations creating a so-called effective SFE enhances. In addition, they [17] believed that at higher strain rates and/or some other loading conditions where high stress levels can be achieved, the SFE might be altered due to the effect of applied stress on the partial dislocation separation. In face-centered cubic (FCC) materials, the applied stress plays a significant role in partial dislocation separation resulting in an effective SFE.

Marcinkowski et al. [18] and later Copley et al. [19] have indicated that in FCC materials with low-SFE, the applied stress changes the equilibrium separation distance of the Shockley partials. Since the partial dislocation separation and the SFE are inversely related, the applied stress creates an effective SFE as experimentally shown in low-SFE austenitic stainless steels [20,21]. Depending on texture and the stress level, the effective SFE can be quite low and lead to twin nucleation [22,23]. It should be emphasized that the present proposed mechanism is difficult to validate experimentally for present steel and requires detailed TEM investigations. The observed mechanical twinning may have two effects on plastic deformation: subdividing the grains (showed in Figure 3(a)) and contributing the amount of plastic deformation due to the twinning shear.

4. Conclusion

The present work focused on an advanced TRIP-TWIP steel with the principal conclusions as are follows:

1. The experimental TRIP-TWIP steel has shown a high comprenssive strength of about 1180 MPa and yield strength of 375 MPa at the 25°C.
2. The TRIP effect accompanying the TWIP effect has been observed from 25 to 100°C.
3. The mechanism of deformation is varied from TRIP-TWIP effects to solely TWIP one in the temperature range of 100°C to 200°C.
4. The high temperature mechanical twinning has been detected up to 1000°C.

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