Tensile Properties and Microstructure of Fe–17Mn–2Al–0.6C TWIP Steel

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Abstract

The tensile properties and microstructure evolution of Fe–17Mn–2Al–0.6C TWIP steel exposed to 80% cold rolling reduction, and annealed at different temperatures were experimentally investigated in order to promote strength–ductility synergy. For this purpose, uniaxial tensile tests were performed on specimens obtained from 80 % cold-rolled sheets, and subsequent annealed at 550, 575, 610, 650, 750, 850, and 1100 ºC, for 30 min. Then, the resulted microstructures were examined by a scanning electron microscopy and a transmission electron microscopy. The results indicated the yield strength and ultimate tensile strength mainly decreased as annealing temperature increased, while the total elongation greatly increased. The variation in the product of ultimate tensile strength and total elongation against yield strength was linked to the annealing temperature. The most evident change in strength and elongation was located between 575 and 610 °C, due to the fraction of recrystallized areas. The fraction of recrystallized areas and grain size increased with increasing annealing temperature. TWIP steel microstructure designs that rely on annealing treatments in the recovery and also lower limits for the partial recrystallization regions, provide opportunities to develop TWIP steel that offer superior combinations of elevated yield strength (i.e., above 1350 MPa), along with considerable product of ultimate tensile strength and total elongation (i.e., above 25 GPa%). To get maximum value for the product of ultimate tensile strength and total elongation, the grain sizes of 7.4 and 16.8 µm for the TWIP steel were suggested, within which it reached more than 75 GPa%.

Keywords: TWIP steel, cold rolling, annealing

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Introduction

High manganese twinning induced plasticity (TWIP) steels have been developed as a category of promising candidate materials that present a high specific strength with robust formability, so that not just lightweight components, but also intricate geometries could be attained within the production process [1, 2].

The value of stacking fault energy (SFE) helps in determining deformation mechanisms in austenitic steels, and this value is dependent on the grain size, chemical composition, and deformation temperature. From a technology viewpoint, TWIP steels show an SFE value ranging from 25 to 45 mJ/m^{-2} at room temperature, by changing the chemical composition, which confers twinning as the main deformation process [3, 4]. TWIP steels consist of high manganese contents that ranged between 15 to 30 wt. %. These steels were seen to be austenitic at room temperature. For ensuring that TWIP steels display twinning as the major deformation mechanism, some other elements such as Al, Si, or C could be included. It is believed that deformation twins act as obstacles against dislocation gliding and increase the work-hardening rate [5, 6].

TWIP steels have been used in many applications related to the automotive industry attributed to the unique combination of the ultimate tensile strength (UTS) and total elongation (TEL). However, several applications of TWIP steels have been discouraged because of their relatively low yield stress (YS) [7, 8]. A high YS is needed for numerous frequent service conditions, whereas high values of UTS and TEL are needed for the infrequent conditions, like impacts, and crash-related components of vehicles [9, 10].

Up to now, many studies have attempted to improve the mechanical properties of TWIP steels. The reports indicated that the cold rolling increased the YS value in TWIP steels, but caused a loss in ductility [11-13]. Hence, it could be challenging to achieve a high strength and ductility combination using the cold rolling technique. Bouaziz et al. [14] stated that the mechanical twins formed by cold rolling were stable for TWIP steels until the recrystallization process. Zamani et al. [15] used the desirability function as an efficient optimization technique for the cold rolling and annealing processes. They suggested the use of an 80% cold rolling reduction, followed by the annealing process at 620 ºC for 30 min. This process yielded the optimal mechanical properties of the steel material, i.e., YS = 914 MPa, UTS = 1061 MPa and TEL = 23%.

Yuan et al. [16] showed the decreasing grain size of a TWIP steel from 28.7 to 2.2 µm resulted in the increasing YS and UTS from 232 and 523 MPa to 410 and 752 MPa, respectively, and the TEL decreased from 54 to 33%. Dini et al. [17] produced nanocrystalline TWIP steel by martensite treatment, having a mean grain size of around 500 nm with high strength (i.e., YS~750 MPa and UTS~800 MPa), and acceptable ductility (i.e., TEL~20%).

In the past few years, the microstructural designs have garnered a lot of attention. A proper design helps in developing materials that display a good combination of strength and ductility. Thus, the microstructural designing process could present a novel technique for increasing the YS value of TWIP steels without altering the chemical composition [18-20].

In this study, the effect of cold rolling and annealing treatment on the microstructure and tensile behavior of the $Fe–17Mn–2Al–0.6C$ TWIP steel has been investigated. Also, two annealing temperature ranges were determined, based on the microstructural control strategy used for obtaining tailored tensile properties, i.e., combining high ductility and strength in Fe–17Mn–2Al–0.6C TWIP steel.

Materials and methods

In this work, a TWIP steel with a chemical composition of Fe–17Mn–2Al–0.6C (wt.%) was used. It was acquired from POSCO Steel, South Korea, in the form of a hot-rolled sheet with 15 mm thickness. Cold rolling reduction of 80% was applied in the direction parallel to the previous hot rolling direction. Tensile specimens were cut along the rolling direction. All tensile tests were conducted at room temperature and a strain rate of 10^{-3} s^{-1} according to ASTM E8M standard with the help of a ZWICK/ROELL tensile test machine. To investigate the effect of annealing treatment, the specimens were annealed at temperatures of 550, 575, 610, 650, 750, and 1100 ºC for 30 min. Then, the recrystallized fractions of the specimens that were annealed at the temperatures ranging between 550 and 650 ºC were evaluated. Scanning electron microscopy (SEM) employed was ZEISS MERLIN SEM. For detailed microstructural observations, a transmission electron microscopy (TEM) operated at 200 kV was used, and the sample preparation was done by the focused ion beam (FIB) method [22, 23].

Results and Discussion

This section is divided into two parts: 1) the effect of the recrystallized volume fraction, and 2) the effect of the grain size on the mechanical properties of the Fe–17Mn–2Al–0.6C TWIP steel.

Effect of recrystallized volume fraction:

Figure 1 shows the temporal changes of the recrystallized volume fraction (Xv) for certain annealing temperatures. As per figure 1, there is an increase in Xv with the rise in annealing temperature, and annealing at 650 ºC for 30 min yields a fully recrystallized microstructure. The recrystallization completion of the present steel occurred at low annealing temperature within a short annealing time (at 650 ºC, for 30 min). It is because the low SFE considerably limits the dynamic recovery (i.e., dislocation annihilation) during cold rolling reduction, which could considerably enhance the nucleation and growth of recrystallized grains during the annealing treatment. This is in agreement with the previous studies [21, 15].

Figure 2 presents the results regarding the effect of the cold rolling and annealing treatment on the tensile behavior of the specimens that were annealed at the temperatures which were lower than those needed for complete recrystallization, i.e. below 650 ºC. Generally, the values of YS and UTS for all the specimens decrease with increasing the annealing temperature, whereas TEL values increase.

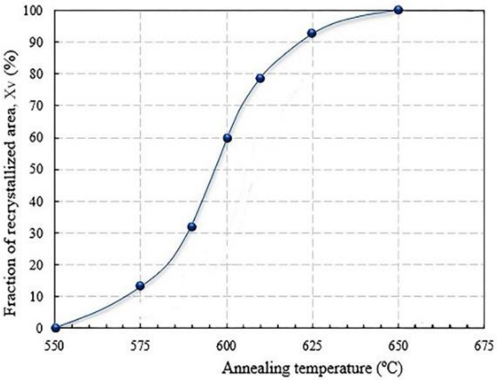

Figure 1: Effect of annealing temperature on the recrystallized volume fraction (Xv) of the Fe–17Mn–1.5Al–0.6C steel cold rolled to 80% reduction

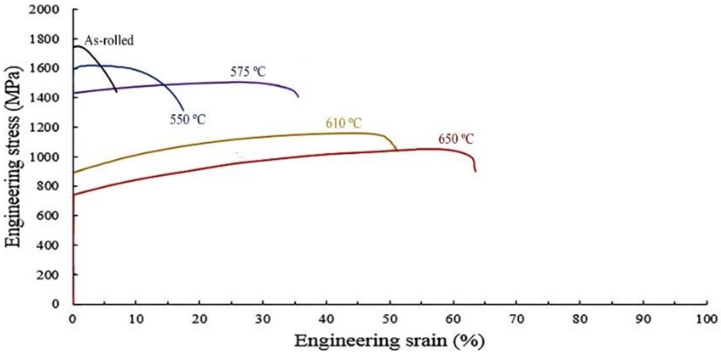

Figure 2: Engineering stress-strain curves of Fe–17Mn–2Al–0.6C TWIP steels with 80% cold rolling reductions annealed at various temperatures for 30 min

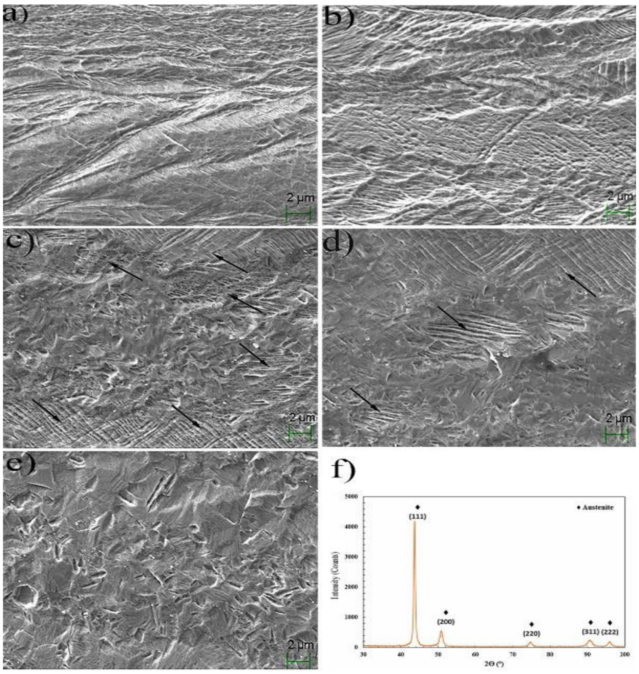

Figure 3: SEM images of the Fe-17Mn-2Al-0.6C TWIP steel cold rolled to 80% reduction and annealed at different temperatures, a) cold-rolled, b) 550 ºC, c) 575 ºC, d) 610 ºC, and e) 650 ºC. Black arrows in (c and d) show twinned deformed areas. f) the XRD pattern of the specimen subjected to 80% cold rolling reduction.

The effect of annealing at different temperatures between 550 and 650 ºC on the microstructure of specimens is displayed in figure 3. As shown in figure 3a, the deformation microstructure that developed in the specimen exposed to 80% cold rolling reduction is characterized by sizeable internal distortions. The deformation twins are blurry and out of contrast, although the density of deformation twins increases with imposing cold rolling reduction, which can be ascribed to elevate the shear band density, consistent with previous reports [11-13].

As shown in figure 3f, the phase transformation did not occur after cold rolling. Therefore, the association between the strength of Fe-17Mn-2Al-0.6C TWIP steel and its microstructural evolutions in cold rolling can be attributed to the increase in the densities of dislocations, shear bands, and deformation twins that accompany with imposing cold rolling, which aligns with previous researches [11-13].

Figures 3b depicts the microstructure of the specimen annealed at 550 ºC which displays no new recrystallized grains arising. Also, the deformation twins feature introduced by cold rolling shows stability during the annealing process, an outcome that aligns with the results of prior research [14, 24, 25]. Therefore, recovery is concurrent. The thermal stability of the deformation twins provides a high level of retained YS and UTS after the recovery annealing treatment. As well, the recovery process reduces the density of dislocations that normally results in regained ductility.

The microstructures of specimens annealed at 575 and 610 ºC contain mixtures of twinned areas and recrystallized grains, i.e. partially recrystallized microstructures, as can be seen in figures 3c and 3d. The mechanical properties of the partially recrystallized specimens were mainly controlled by the contributions of recrystallized to unrecrystallized areas. The presence of deformation twins contributes to the strengthening, and newly recrystallized grains lead to improving ductility, which are the main reasons for the drop of engineering stress-strain curve by increasing the annealing temperature from 575 to 610 ºC, as shown in figure 2. Increasing the annealing temperature from 575 to 610 ºC results in increasing the recrystallized volume fraction from 13 to about 80% (figure 1).

To confirm the presence of mechanical twins in an unrecrystallized area, additional TEM investigations were performed on the specimen annealed at 575 ºC. The inset selected diffraction pattern from the unrecrystallized area confirms the presence of mechanical twins, as can be seen in figure 4. Therefore, the occurrence of recovery and partial recrystallization results in decreased strength and increased elongation, and the specimen annealed at 650 ºC (i.e., fully recrystallized specimen) presents the lowest strength and largest elongation.

Figure 4: TEM image showing the microstructure of the Fe-17Mn-2Al-0.6C TWIP steel annealed at 575 ºC

The product of ultimate tensile strength and total elongation (PSE) of materials (i.e. UTS×TEL) is among the most critical characteristics applied in industrial applications. Material toughness and formability are strongly dependent on the PSE value [10, 20, 26]. On the other hand, a key reason for limiting the immediate application of TWIP steel grades in numerous applications would be the low YS value [7, 8]. Therefore, for a more insightful comparison, the relationship between PSE and YS values of the Fe-17Mn-2Al-0.6C TWIP steel processed with 80% cold rolling reductions and annealed at various temperatures is displayed in figure 5.

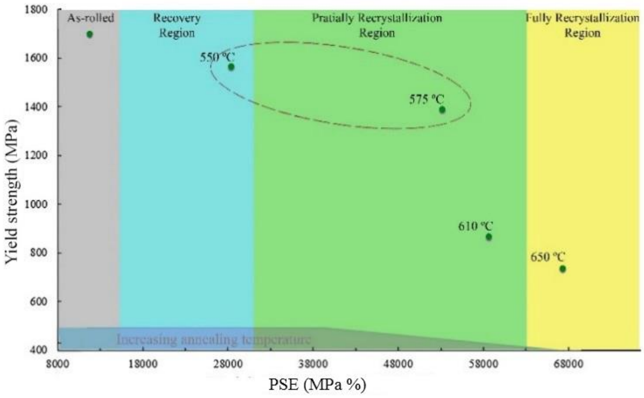

Figure 5: The relation between PSE and YS of 80% cold-rolled specimen annealed at different temperatures

Data point within the yellow area indicates the mechanical properties for the specimen featuring the highest PSE value, but lowest YS value, namely fully recrystallized specimen. The higher PSE of the specimen is mainly a result of greater ductility. PSE values show decreases with an increase in YS approaching the lowest value for PSE in cold-rolled condition (grey area), which is probably caused by decreases in total elongation along with increased YS. Data points within the dashed red circle indicate the mechanical properties for TWIP steels with YS greater than 1350 MPa and with PSE that exceeds 25 GPa·%. The value exceeds that for typical low-carbon commercial automotive sheet steel that features PSE~15 GPa%, or that for TRIP steels featuring PSE~ 20 GPa % [27].

Effect of Grain size:

The SEM images of 80% cold-rolled Fe-17Mn-2Al-0.6C TWIP steel that were annealed at temperatures beyond the level required for completing recrystallization, i.e. 650, 750, 850, and 1100 ºC, are displayed in figure 6. These microstructures comprise polygonal and also equiaxed austenite grains plus some annealing twins. Figure 6 shows that grain sizes increase with increases in the annealing temperature.

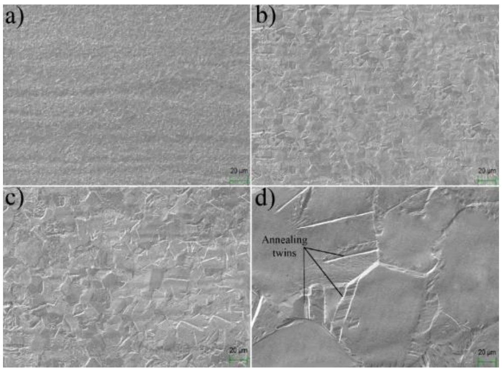

Figure 6: SEM images of the specimens annealed at a) 650 ºC, b) 750 ºC, c) 850 and d) 1100 ºC, annealing twins indicated by arrows

The specimen grain sizes differed within the range of 1.8–87 µm through changes in annealing temperatures in the range of 650–1100 ºC. Tensile behaviors for the four grain sizes examined in this research, i.e. 1.8, 7.4, 16.8 and 87 µm, are displayed in figure 7. As predicted, the values of YS and UTS increased, whereas TEL values decreased with a decrease in grain sizes, which aligns with previous findings [10, 16, 28]. For a better evaluation when finding the optimal mechanical properties in terms of PSE and YS, the relationships between PSE and YS for specimens featuring different grain sizes are displayed in figure 8.

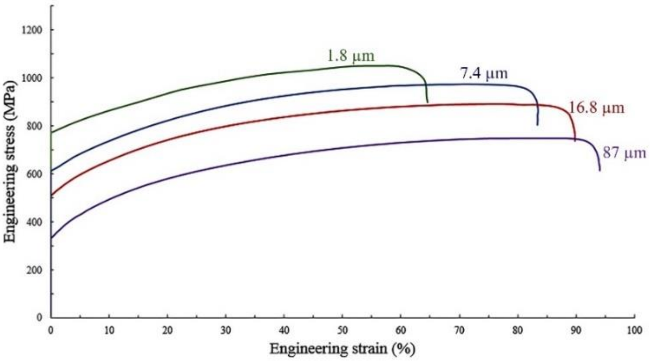

Figure 7: The engineering stress-strain curves for Fe-17Mn-2Al-0.6C TWIP steel with different grain sizes

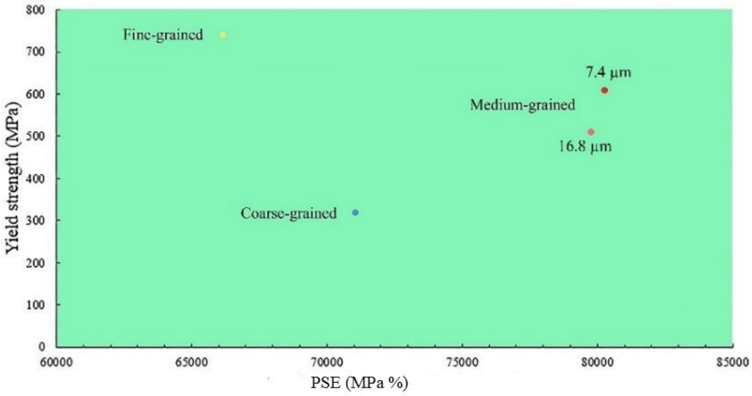

Figure 8: The relation between PSE and YS of specimens with different grain sizes

Red data points indicate the mechanical properties for the medium-grained specimens, i.e. 7.4 and 16.8 µm. The higher PSE of medium-grained specimens results from a good mix of ductility and strength. The PSE values show decreases with increased or decreased grain sizes that approach the lowest values of PSE, for the specimen with a grain size equal to 1.8 µm, which is probably caused by decreases in total elongation. It must be considered, it is generally true for over the range of ductile steel grades, that increasing strength by reducing grain size accompanied by ductility loss [29]. Conversely, an increase in the grain size to 87 µm leads to a drop in strength, although ductility does increase. The current results demonstrate that medium-grained specimens show the best mix of TEL and UTS.

Conclusions

The following conclusions were drawn from this study:

1) The recrystallization start temperature for the Fe–17Mn–2Al–0.6C TWIP steel with 80% cold rolling reduction is about 550 ºC, and the fully recrystallized microstructure was obtained at 650 ºC, for 30 min.
2) Mechanical properties displayed by the partially-recrystallized specimens could be controlled based on the contributions offered by the recrystallized to unrecrystallized areas. Furthermore, the thermal stability of the deformation twins in the unrecrystallized areas helped in retaining the high values of YS and UTS, whereas the recrystallized grains improved the ductility values.
3) Annealing temperature showed a high effect on the grain size, recrystallized volume fractions and thus, on the mechanical properties of the cold-rolled Fe–17Mn–2Al–0.6C TWIP steel. When the annealing temperature increased from 550 ºC to 1100 ºC, the YS and UTS correspondingly decreased from 1570 and 1620 MPa to 320 and 750 MPa, respectively, and the elongation is increased from 17 to 90%.
4) Microstructure designs of the Fe–17Mn–2Al–0.6C TWIP steel that rely on the large cold rolling degree and subsequent annealing treatments in the recovery and also lower limits for the partial recrystallization regions, i.e. the specimens annealed at the temperature range of 550 to 575 ºC, provide opportunities to develop TWIP steel that offers superior combinations of elevated YS, i.e. above 1350 MPa, along with considerable PSE, i.e. above 25 GPa%.
5) Medium-grained specimens, i.e. specimens annealed at the temperature range of 750 to 850 ºC, give the best mixture of strength and ductility, i.e. PSE higher than 75 GPa%.

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Author Contributions

Davood Zamani, Azmah Hanim Mohamed Ariff, Ghasem Dini, conceived of the presented idea. Davood Zamani carried out the experiments. Azmah Hanim Mohamed Ariff and Zainuddin Sajuri encouraged Davood Zamani to investigate a wide range of annealing temperature (i.e. 550-1100 ˚C) and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

Disclosure of Conflict of Interest

The authors declare that they have no conflict of interest.

Compliance with Ethical Standards

Not applicable

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