Texture evolution in medium Mn containing TWIP steel: Experiments and Simulation

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Abstract

In the present work, deformation mechanisms have been studied by evaluating texture and microstructure under cold rolling for medium Mn containing Fe-14Mn-0.5C-3.5Al twinning induced plasticity (TWIP) steel. Rolling has been performed up to true strain ~2.3. Microstructural features reveal that deformation takes place by twinning. Texture evolution shows α-fiber type texture with a continuous α-fiber up to very large strains. Experimentally observed deformation micro-mechanisms have been verified with the visco-plastic self-consistent (VPSC) simulation. Effects of twin volume fraction in texture evolution also been studied by incorporating volume transfer scheme in the VPSC simulation. Simulation results show very good agreement with the experimental results.

Keywords: Texture, microstructure, deformation mechanisms, visco-plastic self-consistent (VPSC) simulation

1. Introduction

The interest in twinning induced plasticity (TWIP) steels has increased over the last few years due to the excellent combination of strength and ductility that renders these materials suitable for many applications. TWIP steels exhibit very high strain hardening rate due to the formation of very high fraction of deformation twins which can lead to dynamic Hall-Petch effect [1-3]. TWIP steels are high manganese containing steels with face centred cubic (FCC) crystal structure. In conventional TWIP steels, the manganese content generally varies between 20 – 30 weight percent. Although such a high Mn content leads to some very desirable properties, it also poses a challenge in materials production. The addition of Mn to such a high extent leads to delayed cracking of the materials after processing to shapes [4]. This could be detrimental for industrial applications. Therefore, it has been proposed to reduce the Mn content in TWIP steels to lower levels. The addition of Al also helps in reducing the tendency for delayed cracking. Since the Mn content in TWIP steels influences the stacking fault energy (SFE) and so does Al-addition turn dictates deformation micromechanisms, it is important to examine the effect of SFE in the case of lower Mn Al-containing TWIP steels [5]. SFE is reported to play a major role in twin mediated deformation mechanisms [6, 7]. It has been reported that for steels with SFE in the range of 20-50 mJm⁻², deformation take place by twinning whereas for materials with SFE below 15 mJm⁻².
deformation is governed by martensitic transformation [8, 9]. The critical value of SFE for the transition from strain induced martensite transformation to mechanical twinning has been reported as > 9 mJm$^{-2}$, and the maximum value of SFE for the formation of ε-martensite is 12 mJm$^{-2}$ [7].

It is well known that texture development in FCC materials strongly depends on the SFE. Materials with higher SFE (i.e. Al, Ni and Cu) do not undergo by twinning during deformation and develop a strong Cu-type texture (comprises of Brass, Cu and S components), while the materials with low SFE (i.e. Ni-60Co, Cu-30Zn and Ag) generally deform by twinning and develop Brass-type texture (comprises of Goss and Brass components) [10-13]. Recently, Madhavan et al. [14-16] reported Cu-type to Brass-type texture transition in some Ni-Co alloys, which have SFE in the same range as TWIP steels, at large rolling strains. TWIP steels are categorized as low SFE materials.

In the present investigation, the evolution of deformation texture and microstructure has been carried out for a TWIP steel with the composition Fe-14Mn-0.5C-3.5Al to understand the deformation mechanisms during rolling to large strain. The SFE of this steel is approximately ~50 mJm$^{-2}$. In order to understand the individual contribution of slip-twin systems in texture evolution visco-plastic self-consistent (VPSC) simulation was performed.

2. Experiments

2.1 Material and processing

TWIP steel with a composition Fe-14Mn-0.5C-3.5Al (wt%) was melted in an arc melting furnace under an argon atmosphere. The charge was melted several times to get adequately homogeneous composition. As-melted button shaped sample was homogenized in a furnace at 1100°C for 5 hrs under high vacuum (<10$^{-5}$ mbar). The homogenised button was cross rolled in many steps to 50 % reduction in thickness and then annealed at 830°C for 30 minutes. An equiaxed microstructure with average grain size ~50 µm was obtained after this treatment. The so-obtained plate was treated the starting material. The starting plate was rolled to thickness reductions ~ 40%, 70% and 90% and subsequently subjected to investigations pertaining to texture and microstructural evolution.

2.2 Characterizations

Structural characterization of the material at different stages was carried out by X-ray diffraction. Textures were measured for the starting material as well as for the cold rolled samples using a Bruker D8 discover diffractometer based on the Schultz reflection geometry, equipped with a four circle goniometer employing Co k$_\alpha$ ($\lambda=0.1791$ nm) target. Four incomplete pole figures (111), (200), (220) and (311) were measured. Measurement was performed at the mid section parallel to the rolling plane. All the measurements were carried out in the range phi=0-360° and chi=0-75° with a step size 5° and exposure time 5 sec. The orientation distribution functions (ODFs) were calculated from the four measured pole figures using JTex software [17]. Microstructural characterization was performed in a FEI ESEM-Quanta scanning electron microscope (SEM), equipped with electron backscatter diffraction (EBSD) system. EBSD scans were recorded on the RD-ND plane (the plane normal to TD).
The rolled samples were metallographically polished followed by electropolishing. Struers ElectroPol-5 electropolishing system was used for EBSD sample preparation. The analysis of the EBSD scans was done using TSL-OIM™ software. The mechanical properties were evaluated by carrying out tensile tests on the annealed strips. For tensile tests, flat dog-bone shaped samples with 6 mm gauge length, 2 mm width and ~0.7 mm thickness were used. Tensile tests were carried out in a Servo-hydraulic UTS machine at room temperature with strain rate of $10^{-3}$ s$^{-1}$. Tests were carried out till failure.

3. Visco-plastic self-consistent simulation

Visco-plastic self consistent (VPSC) model was used to investigate the contribution of different microscopic deformation mechanisms and consequent texture evolution. The details VPSC model is given in Ref. [18]. In the present simulation, perfect slip and twinning systems are have been activated to account for the deformation according to the critical resolved shear stress (CRSS) associated with each of the deformation process. Bronkhorst type hardening law was used to account for microscopic hardening [19]. Bronkhorst hardening law can be written as:

$$H_{ij} = q_{ij} h_0 \left(1 - \frac{\tau_i}{\tau_{sat}}\right)^a$$

where $h_0$ and $a$ are hardening exponents, $\tau_{sat}$ is saturation stress. The $q_{ij}$ is symmetric hardening matrix which expresses interaction between different slip systems. Geometric configuration of different slip systems are co-planar slip ($q_1$), collinear slip ($q_2$), slip with perpendicular Burgers vector ($q_3$) and for all other cases ($q_4$).

Volume transfer scheme was incorporated in simulation to adopt the statistical approach in calculation to account the twin volume effects in texture evolution [20]. According to this scheme, twin volume transfer from a mother grain to the given twin during at a time increment $\Delta t$, can be expressed as:

$$\Delta V^s = V_{mother} \times \frac{\dot{\gamma}_t \Delta t}{\gamma_{twin}}$$

where, $V_{mother}$ is the volume of mother grain, $\dot{\gamma}_t$ is the rate of twinning, $\gamma_{twin}$ is twin shear. Single twin variant was activated in the present simulation. The advantage of this scheme over the predominant twin re-orientation (PTR) is that it accounts for the thickening of twins as well as it considers the twin morphology [21]. Twin boundary rotation during strain also can be accounted for in volume transfer method, which helps in approaching towards more realistic situation.

4. Results and discussion

4.1 Microstructural evolution during rolling

Fig. 1 displays the microstructures of the starting material as well as the deformed samples. Starting microstructure shows typical recrystallized equiaxed grain structure with high fraction of annealing twins (Fig. 1a). The 40% cold deformed microstructure, however,
reveals the presence of deformation twins and a large strain gradient in some grain. Some region in the microstructure could not get indexed properly due to very high strain localization (Fig. 1b). Localized strain distribution is depicted using grain reference orientation deviation (GROD) plot, which represents the misorientation development inside the grain due to simultaneous generation of geometrically necessary dislocations (GNDs), that are required to accommodate the imposed plastic strain. GROD plot indicates the presence of maximum strain at near to grain boundary (Fig. 1c). Large strain gradient inside the grains reveals that plastic deformation does not solely takes place by twinning, rather dislocation slip also play a crucial role. Another important observation is that the grains, which does not deformed by twinning, show higher GROD value, whereas an opposite trend is observed for the twinned grains. The characterization of the deformed microstructure has been carried out up to 40% rolling reduction, beyond which the microstructure could not be indexed properly in EBSD. The presence of twins in microstructure has been characterized by plotting misorientation distribution across the grains. Misorientations of ~60° with matrix orientation indicates the presence of twins in microstructure (Fig. 1d).
4.2 Evolution of deformation texture

The $\Phi_2 = 0^\circ$, $45^\circ$ and $65^\circ$ sections of the orientation distribution function (ODF) plots for the deformed samples are shown in Fig. 2. The ODF sections show $\alpha$-fiber type texture in all the cold rolled samples at early stages of rolling deformation. For intermediate to large rolling strain, maximum intensity is located at Goss ({110}<001>) and Goss/Brass position along $\alpha$-fiber, which suggests texture evolution as Brass-type. Negligible intensities observed at Cu ([112]<111>) and S ([123]<634>) positions. Many authors have reported Bs-type texture evolution during rolling in high Mn TWIP steels [22-24]. In the ODFs, in addition to $\alpha$-fibre, a weak $\gamma$-fiber ([111]||ND) is also observed in the $\Phi_2 = 45^\circ$ section. The $\gamma$-fiber develops at medium deformation level (~50-70% rolling reduction). The $\gamma$-fiber intensity remains very weak up to large deformation levels. The development of a weak $\gamma$-fiber is reported by many authors earlier for high Mn TWIP steels [22, 25] and also for some other non-ferrous low SFE materials [14, 15, 26, 27].

Fig. 2: $\Phi_2 = 0^\circ$, $45^\circ$ and $65^\circ$ ODF sections of starting material and 40% to 90% cold rolled TWIP steel. Some important rolling texture components and fibres are marked (in red colour) in ODF sections.

4.3 Visco-plastic self-consistent (VPSC) simulation

Texture simulation was carried out to understand the individual contributions of slip and twinning in texture evolution. A random texture with spherical grain shape was taken as starting texture. Self-consistent mode with strain rate sensitivity 0.16 was used for texture simulation. As mentioned earlier, Bronkhorst type hardening and symmetric latent hardening parameters are listed in Table 1. Fig. 3 shows the simulated texture for 40%, 70% and 90%
rolling reductions with CRSS ratio for twin to slip as 1.25. In the present case, texture simulation has been tuned with experimentally determined tensile stress-strain curve (Fig. 4a). A very good fit between tensile data and simulated stress-strain curve is observed. Twin/slip activity ratio reveals the maximum twin activity at ~30% reduction level, then decreases and above 50% reduction levels twinning gets saturated (Fig. 4b). Fig. 4c shows the imposed twin volume fraction in texture evolution. In the present case, approximately 45% twin volume has been incorporated for 90% rolling reduction. Twin deviation from the ideal position was (60° misorientation with respect to matrix) has also been calculated, and the results show a continuous deviation from the ideal position with rolling strain (Fig. 4d).

**Table 1:** Bronkhorst hardening, symmetric hardening parameters and velocity gradient for rolling

| \( \tau_{\text{sat}} \) | \( \tau_0 \) | \( h_0 \) | a | \( q_1 \) | \( q_2 \) | \( q_3 \) | \( q_4 \) | Velocity gradient |
|---|---|---|---|---|---|---|---|---|
| 2000 | 3.0 | 1500 | 5.25 | 1 | 1.2 | 2.0 | 1.5 | \[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & -1
\end{bmatrix}
\] |

The simulated textures are in very good agreement with the experimentally observed texture. In the simulated texture, maximum intensity is located at Goss and Brass positions throughout the deformation level. Weak Cu and S components are also observed similar to experimentally evaluated texture. Simulated results indicate significant role of twinning for Brass-type texture evolution in TWIP steels. Earlier researchers have performed texture simulation using VPSC modelling with contributions of slip and twinning on texture evolution and have reported that twinning plays a predominant role in the formation of Brass-type texture [22, 23, 28].

**Fig. 3:** Simulated \( \Phi_2 = 0^\circ, 45^\circ \) and \( 65^\circ \) sections of ODF for 40% to 90% cold rolled TWIP steel.
5. Conclusions

The evolution of deformation texture and microstructure were studied for a medium Mn TWIP steel with Al. A combination of experimental and crystal plasticity simulation was employed to understand the deformation behaviour of this alloy. Following are the important conclusions can be drawn from the analyses experimental and simulation results:

1. Texture evolution in medium Mn Al-containing TWIP steels is brass type with continuous $\alpha$-fiber throughout the deformation regime. The intensity maxima are located at Goss and Brass positions.
2. Microstructure of the deformed material exhibit deformation twinning as well as large strain gradient inside grains which indicates both slip and twins take part in plastic deformation, with their relative contributions varying with strain.
3. Simulated texture shows a very good agreement with the experimentally observed texture. Continuous shortening of $\alpha$-fiber observed in simulated texture which also observed in experimental texture.

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