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Abstract. Modeling the effect of deformation on mechanical properties of a Fe-23Mn-0.3C-1.5Al (in wt. %) TWIP steel subjected to extensive cold rolling was performed. The approach including Hall-Petch relation and dislocation strengthening was used for the determination of the strength increment with deformation. Distance between twin boundaries was considered to be the mean free path for dislocation glide in the Hall-Petch relationship. The rate of dislocation accumulation in the TWIP-steel was calculated via the X-ray diffraction (XRD) measurements and compared with direct transmission electron microscopy (TEM) measurements by counting individual dislocations crossing the thin foil surface after small reductions. It was shown that a decrease of the dislocation mean free path by formation of twins with nanoscale thickness is of less importance for the strengthening than an increase of the dislocation density, which was shown to be the major strengthening mechanism. This suggested that twin boundaries were more readily transparent and, therefore, provided less strengthening as compared to ordinary grain boundaries. The developed model has shown a good agreement with the experimental data.

1. Introduction
During last years high-Mn steels with twinning induced plasticity (TWIP) effect have been attracted great attention as a new group of materials for structural applications in the automotive industry due to their excellent combination of strength and elongation [1–3]. TWIP steels usually have Mn content of 18–30 wt. % and additional alloying elements such as C, Al and Si. Numerous studies [4-8] have been carried out to understand the work hardening behavior of TWIP steels. It is believed that formation of mechanical twins during deformation leads to an increase in the instantaneous work hardening rate. In other words, twin boundaries act as strong obstacles for dislocation movement. Such behavior results in the ductility improvement by the delay of local necking [9–11]. Several models have been developed for high-Mn TWIP steels in order to describe the evolution of mechanical properties with strain [11–14]. In most of them the strengthening contribution due to the formation of mechanical twins was considered via a reduction of the mean dislocation free path (i.e., the dynamic Hall–Petch effect). Also, it was recently confirmed that twinning is the most important mechanism explaining the high strain-hardening of TWIP steels [15,16]. However, the proposed models describe the evolution of mechanical properties only at rather low strains, e.g. below 0.6 true strain at fracture during tensile test. The aim of the present study was to develop a model capable to describe the change of mechanical properties during cold rolling of high-Mn TWIP steel up to large strains.

2. Experimental
A forged plate of a Fe-23Mn-0.3C-1.5Al steel with the chemical composition given in Table 1 was hot rolled from 50 to 10 mm thickness at 1150°C and then annealed at the same temperature for 1 hour. This treatment resulted in the development of a uniform microstructure with an average grain size of 24 µm. The plate samples were cold rolled to final thickness of 8, 6, 4 and 2 mm (rolling reductions were 20, 40, 60 and 80%, respectively). The rolling direction was the same as that in the hot rolling. The dislocation density was determined by analysis of X-Ray diffraction profiles and estimated by counting...
individual dislocations crossing the thin foil surface by method described elsewhere [17,18]. An ARL-Xtra diffractometer operated at 45 kV and 35 mA, and the diffraction profiles were collected using Cu Kα radiation. Average values of the crystallite size d’ and microstrains <ε50> were estimated on the basis of the Williamson-Hall plot [19] given by given by the eq. (1):

\[ \frac{\beta_s \cos \Theta}{\lambda} = \frac{2 < \varepsilon_{50}^2 > \sin \Theta}{\lambda} + \frac{K}{d'} \]  

(1)

where Θ is Bragg angle, K is the Scherrer constant and \( \beta_s \) is the full width at the half maximum height (FWHM) of Kα line with the correction of instrumental line broadening. In this study, the FWHM values were measured for γ–Fe (111) and (222) reflections. The instrumental line broadening was obtained from the FWHM value (\( \beta_i \)) of Kα1 line of an annealed silicon powder and removed from measured FWHM value (\( \beta_m \)) of Kα1 line of TWIP-steel on the following eq. [20]:

\[ \beta_s^2 = \beta_m^2 - \beta_i^2 \]  

(2)

The value of the dislocation density \( \rho \) by XRD was calculated from the average values of the crystallite size d’ and microstrain <ε50> by using the following relationship [21]:

\[ \rho = \frac{3\sqrt{2\pi} < \varepsilon_{50}^2 >}{d'b} \]  

(3)

where b is the Burgers vector (\( b = a/\sqrt{2} \) for FCC structures, a is the lattice parameter). Two specimens were used for each condition. For structural characterization by a transmission electron microscope (TEM) thin foils of 3 mm diameter were cut out parallel to the RD-ND plane and grinded to 0.1 mm thickness. Then the discs were polished using a double jet TENUPOL-5 electrolytic polisher at voltage of 20 V at room temperature. An electrolyte contained 10% perchloric acid and 90% acetic acid. The foils were examined using the JEOL JEM-2100 TEM operated at an acceleration voltage of 200 kV. The distance between deformation twins was measured by the mean linear intercept method, in which the direction of a measuring line was normal to the twin boundaries. A least 10 TEM micrographs were used for each specimen to obtain relevant statistics. Tensile tests were carried out by using the Instron 5882 testing machine at an ambient temperature on specimens with a gauge length of 16 mm and cross section of 1.5 mm × 3 mm cut out parallel to the rolling plane. The samples were tested at a strain rate of 2×10^{-3} s^{-1} with tensile axis parallel to the rolling axis. Two tensile specimens were used for each condition.

Table 1. Chemical composition of the investigated steel

| Element | C  | Mn  | Al  | Si  | Cr  | S   | P   | Fe  |
|---------|----|-----|-----|-----|-----|-----|-----|-----|
| [wt pct]| 0.304 | 23.1 | 1.5 | 0.09 | 0.08 | 0.006 | 0.017 | bal. |

3. Results and discussion

The Fe-23Mn-0.3C-1.5Al TWIP-steel in the annealed state exhibited a relatively low yield stress (YS) of 235 MPa and medium ultimate tensile strength (UTS) of 660 MPa alongside with the excellent total elongation of 0.67 (given as true strain) (Fig. 1). The cold rolling led to increase in both the YS and ultimate tensile strength significantly, whereas ductility decreased with increasing the rolling reduction. The YS, UTS and total elongation depending
on rolling reduction are summarized in table 2 (deformed specimens denoted as CRx0, where CR means "cold rolled" and xo indicate a reduction degree in %). The rolling strain is given as true strain.

![Stress-strain curves](image)

**Fig. 1 - The stress-strain curves of the Fe-23Mn-0.3C-1.5Al steel**

| Specimen | Rolling strain | YS, MPa | UTS, MPa | Total elongation |
|----------|----------------|---------|----------|-----------------|
| Initial  | 0              | 235     | 660      | 0.67            |
| CR20     | 0.22           | 690     | 840      | 0.29            |
| CR40     | 0.51           | 1030    | 1150     | 0.07            |
| CR60     | 0.91           | 1240    | 1400     | 0.05            |
| CR80     | 1.61           | 1400    | 1580     | 0.04            |

An approach for determination of strength increment with deformation including Hall-Petch relation and dislocation strengthening was used. According to this approach strength increment was calculated as

$$\sigma_{0.2} = \sigma_0 + \frac{K_f}{D} + \alpha M G b \sqrt{\rho}$$

(4)

where $\sigma_0$ is the friction stress of untwinned matrix, $K_f$ is the strengthening coefficient, $D$ is the mean free path for dislocation glide, $\rho$ is the dislocation density, $\alpha$ is a constant, $M$ is the average Taylor factor, $G$ is the shear modulus, and $b$ is the Burgers vector. The distance between twin and grain boundaries was considered to be the mean free path for dislocation glide in the Hall-Petch relationship, $D$. The rate of dislocation accumulation in the TWIP-steel was calculated using the results of previous X-ray diffraction (XRD) measurements [22] and compared with direct transmission electron microscopy estimation by counting individual dislocations crossing the thin foil surface after small reductions. The experimental values of the distance between twins and the dislocation density estimated by XRD and TEM are given in Table 3. Specimens subjected to high reduction degree were characterized by a high density of deformation twins along with a high dislocation density, such that the dislocation densities were difficult to estimate directly by means of TEM.
Table 3 – Experimental parameters of TWIP-steel microstructure

| Specimen | Distance between boundaries, m | ρ [XRD], m⁻² | ρ [TEM], m⁻² | Crystallite size d’, m |
|----------|-------------------------------|-------------|-------------|----------------------|
| Initial  | 2.4×10⁻⁵                     | 10¹⁴        | 1.05×10¹⁴   | 1.2×10⁻⁷            |
| CR20     | 5.7×10⁻⁷                     | 1.86×10¹⁵   | 1.06×10¹⁵   | 7.2×10⁻⁸            |
| CR40     | 1.83×10⁻⁷                    | 1.86×10¹⁵   | -           | 3.5×10⁻⁸            |
| CR60     | 1.0×10⁻⁷                     | 3.44×10¹⁵   | -           | 4.6×10⁻⁸            |
| CR80     | 3.2×10⁻⁸                     | 4.47×10¹⁵   | -           | 3.9×10⁻⁸            |

The measured dislocation densities were approximated by function of exponential growth to maximum as

\[ \rho = \rho_0 + \beta (1 - \exp(-n\epsilon)) \] (5)

where \( \rho_0 \) is the dislocation density in undeformed material, \( \epsilon \) is the rolling strain and \( \beta \) and \( n \) are coefficients. The best fit to experimental values was obtained with fitting parameters listed in Table 4. Comparison of experimental and calculated data is shown on Fig. 2.

Assuming that the grain and twin boundaries are main obstacles for dislocation glide, \( D \) in the Hall-Petch relation can be written as [10,23]

\[ \frac{1}{D} = \frac{1}{d} + \frac{1}{l} \] (6)

where \( d \) is the mean grain size and \( l \) is the distance between twin boundaries. Taking into account the contribution of specimen’s thickness reduction by rolling, Eq. 6 will be written as

\[ \frac{1}{D} = \left( \frac{1}{d} + \frac{1}{l} \right) \exp(ke) \] (7)

where \( k \) is the fitting coefficient. According to Fullman’s analysis [24], the distance between twins is linked to the twin content \( f \) and the thickness of twin lamella, \( t \), by the relation:

\[ l = \frac{1}{2t} \times \frac{f}{1-f} \] (8)

To describe the evolution of distance between twins, simplified equation proposed by Bouaziz [13] was used:

\[ f = f_0 (1 - \exp(-m\epsilon)) \] (9)

where \( f_0 \) is the maximum fraction of twinned area and \( m \) is the fitting parameter.

As seen in Fig. 3, there is excellent agreement between the mean free path of dislocations calculated according to this model and the current experimental data.
Table 4—values of constants used in Eqs. 5-9

| ρ₀, m⁻² | β, m⁻² | n   | F₀   | t, m  | k   | m   |
|---------|--------|-----|------|-------|-----|-----|
| 10¹⁴    | 5.35×10¹⁵ | 1.1 | 0.65 | 2×10⁻⁸ | 0.6 | 0.43 |

Fig. 2 – Experimental (dot) and calculated (line) values of dislocation densities of the present TWIP-steel.

After substitution of ρ and D from Eq. 5 and Eq. 7 into Eq. 4 and coefficients from Table 4, the flow stress can be written as:

\[
\sigma_{0.2} = \sigma_0 + K_y \left( \frac{\exp(16.601 + 0.6e) - \exp(16.5985 + 0.17e)}{0.35 + \exp(-0.43(1 + e))} \right)^{-0.5} + \alpha M G b \sqrt{10^{14} + 5.35 \times 10^{15}(1 - \exp(-1.1e))} \]  

(10)
The best agreement between the flow stress by Eq. 4 and the experimental data was achieved with constants given in Table 5, though parameters listed in Table 4 were used for the best fit to dislocation densities from experiment. It should be noted that dislocation densities calculated with $\rho_0$, $\beta$ and $n$ from Table 5 have only minor difference with values measured with constants from Table 4.

Table 5 – values of constants used in Eq. 4

| $\rho_0$, m$^{-2}$ | $\beta$, m$^{-2}$ | $n$ | $\sigma_0$, MPa | $K_0$, MPa×m$^{0.5}$ | $\alpha$ | $M$ | $G$, MPa | $b$, m |
|------------------|------------------|----|-----------------|-------------------|--------|-----|--------|-------|
| $5\times10^{13}$ | $5.75\times10^{15}$ | 1.03 | 110             | 0.025             | 0.33   | 3   | 72000  | $2.4 \times 10^{-10}$ |

Hence, Eq. 4 can be written as:

$$\sigma_{0.2} = 110 + \left( \frac{\exp (9.223 + 0.6e) - \exp (9.2207 + 0.17e)}{0.35 + \exp (-0.43(1 + e))} \right)^{-0.5} + 17.1\times10^7 \sqrt{58 - \exp (4.05 - 1.03e)}$$

(11)

Thereby strength contribution by the Hall-Petch effect is much less than that of the dislocation density. Fig. 4 illustrates contribution of each mechanism to the tensile strength of the Fe-23Mn-0.3C-1.5Al TWIP-steel and Fig. 5 shows a good agreement between the calculated and experimental data. Here $\sigma_{HP} = K_0D^{-0.5}$ and $\sigma_{disl} = \alpha MGb^{0.5}$.

Fig. 4 – Calculated strength contribution of the present TWIP-steel by different mechanisms.
Eq. 11 represents a modified type of the equation proposed by Voce [25]:

\[
\sigma = B - (B - A)\exp(-n\epsilon)
\]  

(12)

The same type of relationship was found by Nguyen Q. Chinh and T.G. Langdon [26] in pure aluminum and pure copper over a wide range of strains through a combination of conventional tensile and compressive testing and the use of samples processed by equal-channel angular pressing (ECAP) to high strains at different temperatures.

4. Conclusions

1. Modeling the effect of deformation on mechanical properties of a Fe-23Mn-0.3C-1.5Al (in wt. %) TWIP steel subjected to extensive cold rolling was addressed. Cold rolling led to an increase of dislocation density and decrease of dislocation mean free path resulted from mechanical twinning and rolling reduction. Dislocation density evolution can be written as \( \rho = 5 \times 10^{13} + 5.75 \times 10^{13} \times (1 - \exp(-1.03e)) \) and dislocation mean free path dependence on rolling strain can be written as

\[
D = \frac{0.35 + \exp(-0.43(1 + e))}{\exp(16.601 + 0.6e) - \exp(16.5985 + 0.17e)}
\]

2. The model including Hall-Petch relation and dislocation strengthening was proposed and showed good agreement with experimental data.

3. According to the proposed model a decrease of the dislocation mean free path by mechanical twinning had less influence on strengthening of TWIP-steel in comparison with the dislocation strengthening.

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