Data Article

Data related to dislocation density-based constitutive modeling of the tensile behavior of lath martensitic press hardening steel

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A B S T R A C T

The data presented in this article are related to the research article entitled “On the plasticity mechanisms of lath martensitic steel” (Jo et al., 2017) [1]. The strain hardening behavior during tensile deformation of a lath martensitic press hardening steel was described using a dislocation density-based constitutive model. The Kubin–Estrin model was used to describe strain hardening of the material from the evolution of coupled dislocation densities of mobile and immobile forest dislocation. The data presented provide insight into the complex deformation behavior of lath martensitic steel.

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The strain hardening behavior during tensile deformation of a lath martensitic press hardening steel (PHS) was described using a dislocation density-based constitutive model. The Kubin–Estrin model was used to describe strain hardening of the material from the evolution of coupled dislocation densities of mobile and immobile forest dislocation. Two models with different parameter values are presented, and the results include stress–strain curves and the evolution of mobile and forest dislocation density with strain, calculated by the models. The parameter values used for modeling are presented in a table.

2. Experimental design, materials and methods

A cold-rolled 0.35 wt% C PHS was used [1]. The tensile samples were austenitized and then quenched to room temperature in order to make fully martensitic microstructure. The specimens were tested in tension in an electromechanical universal testing machine using a strain rate of 10^{-3} s^{-1}. The experimental true stress-strain curve of the as-quenched PHS is shown in Fig. 1.

The conventional yield strength (YS), i.e. 0.2% offset stress, of lath martensitic steel is generally high as compared to other steels. However, micro-yielding can occur at stresses lower than the 0.2% offset stress. Due to the absence of a clear yield point in the flow curve of lath martensitic steel, the 0.2% offset YS is considered as the YS of the material in the present work. The equation proposed by Galindo-Nava and Rivera-Díaz-del-Castillo was used to calculate the YS of the PHS [2]:

\[ \sigma_{\text{Martensite}} = \sigma_0 + \frac{300}{\sqrt{d_{\text{block}}}} + 0.25MGb\sqrt{\rho} \] (1)
σ₀ is contributions from Peierls stress and solid solution strengthening, \( M \) is the Taylor factor, \( G \) is the shear modulus, \( b \) is the magnitude of the Burgers vector and \( \rho \) is the total dislocation density. The equation for \( \sigma_0 \) derived by Rodriguez and Gutierrez [3] yielded 201 MPa considering the chemical composition of the investigated PHS. The present work did not consider solid solution hardening by carbon. Using the block size of 500 nm, the second term in Eq. (1) was estimated to be 424 MPa. The average initial forest dislocation density in the PHS was estimated to be \( 2.21 \times 10^{15} \text{ m}^{-2} \) by subtracting the sum of contributions from the first term, i.e. 201 MPa, and the packet size strengthening term, i.e. 424 MPa, from the experimental YS, 1354 MPa. The estimated dislocation density is in a reasonable agreement with the measured dislocation density of a Fe-0.4 wt\%C martensitic steel, i.e. \( 1.42 \times 10^{15} \text{ m}^{-2} \), reported by Morito et al. [4].

The Kubin–Estrin model was used to describe strain hardening behavior of the PHS from the evolution of coupled densities of mobile dislocations, \( \rho_m \), and immobile forest dislocations, \( \rho_f \) [5,6].

\[
\frac{d\rho_m}{d\epsilon} = M\left[\frac{C_1}{b^2}\left(\frac{\rho_f}{\rho_m}\right) - C_2\rho_m - \frac{C_3}{b}\sqrt{\rho_f}\right]
\]

\[
\frac{d\rho_f}{d\epsilon} = M\left[2\rho_m + \frac{C_3}{b}\sqrt{\rho_f} - C_4\rho_f\right]
\]  

In these equations, \( C_1 \) specifies the magnitude of the dislocation generation term, with forest obstacles acting as pinning points for fixed dislocation sources. \( C_2 \) takes into account the mobile dislocation density decrease by interactions between mobile dislocations. \( C_3 \) describes the immobilization of mobile dislocations assuming a spatially organized forest structure. \( C_4 \) is associated with dynamic recovery by rearrangement and annihilation of forest dislocations by climb or cross slip. \( C_2 \) and \( C_4 \) account for thermally activated mechanisms such as cross-slip and climb [5].

The parameters \( C_1, C_2, C_3 \) and \( C_4 \) used in the present work are listed in Table 1. The parameters in original Kubin–Estrin model were chosen based on typical FCC metals and alloys [6]. In the present work, a much higher values of \( C_3 \) were used to describe the high initial work hardening of PHS as compared to the value in the original Kubin-Estrin model. The numerical values of the parameters were \( G = 81.6 \text{ GPa}, b = 0.248 \text{ nm} \) and \( M = 3.067 \).

Table 1
Parameter values used for numerical simulations.

| Parameters          | Original Kubin–Estrin model | Model 1   | Model 2   |
|---------------------|----------------------------|-----------|-----------|
| \( \frac{C_1}{b^2} \) | \( 10^{15}/3 \)             | \( 10^{15}/3 \) | \( 10^{15}/3 \) |
| \( C_2 \)           | 0.606                       | 1.42      | 0.7       |
| \( \frac{C_3}{b} \) | \( 10^9/3.3 \)              | \( 9 \times 10^8 \) | \( 9 \times 10^8 \) |
| \( C_4 \)           | 3.33                        | 7         | 3.5       |

Here, \( \sigma_0 \) is contributions from Peierls stress and solid solution strengthening, \( M \) is the Taylor factor, \( G \) is the shear modulus, \( b \) is the magnitude of the Burgers vector and \( \rho \) is the total dislocation density. The equation for \( \sigma_0 \) derived by Rodriguez and Gutierrez [3] yielded 201 MPa considering the chemical composition of the investigated PHS. The present work did not consider solid solution hardening by carbon. Using the block size of 500 nm, the second term in Eq. (1) was estimated to be 424 MPa. The average initial forest dislocation density in the PHS was estimated to be \( 2.21 \times 10^{15} \text{ m}^{-2} \) by subtracting the sum of contributions from the first term, i.e. 201 MPa, and the packet size strengthening term, i.e. 424 MPa, from the experimental YS, 1354 MPa. The estimated dislocation density is in a reasonable agreement with the measured dislocation density of a Fe-0.4 wt\%C martensitic steel, i.e. \( 1.42 \times 10^{15} \text{ m}^{-2} \), reported by Morito et al. [4].

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\[
\frac{d\rho_m}{d\epsilon} = M\left[\frac{C_1}{b^2}\left(\frac{\rho_f}{\rho_m}\right) - C_2\rho_m - \frac{C_3}{b}\sqrt{\rho_f}\right]
\]

\[
\frac{d\rho_f}{d\epsilon} = M\left[2\rho_m + \frac{C_3}{b}\sqrt{\rho_f} - C_4\rho_f\right]
\]  

In these equations, \( C_1 \) specifies the magnitude of the dislocation generation term, with forest obstacles acting as pinning points for fixed dislocation sources. \( C_2 \) takes into account the mobile dislocation density decrease by interactions between mobile dislocations. \( C_3 \) describes the immobilization of mobile dislocations assuming a spatially organized forest structure. \( C_4 \) is associated with dynamic recovery by rearrangement and annihilation of forest dislocations by climb or cross slip. \( C_2 \) and \( C_4 \) account for thermally activated mechanisms such as cross-slip and climb [5].

The parameters \( C_1, C_2, C_3 \) and \( C_4 \) used in the present work are listed in Table 1. The parameters in original Kubin–Estrin model were chosen based on typical FCC metals and alloys [6]. In the present work, a much higher values of \( C_3 \) were used to describe the high initial work hardening of PHS as compared to the value in the original Kubin-Estrin model. The numerical values of the parameters were \( G = 81.6 \text{ GPa}, b = 0.248 \text{ nm} \) and \( M = 3.067 \).
Two models were analyzed. In the first model, i.e. model 1, high values of $C_2$ and $C_4$ were used since BCC metals and alloys generally have higher cross-slip activity as compared to FCC metals and alloys. As shown in Fig. 1(a), the experimental flow stress is much higher than the calculated flow stress by model 1. In the second model, i.e. model 2, lower values of $C_2$ and $C_4$ were used in order to match the experimental and calculated flow stresses. Neither model could however describe the high initial work hardening rate shown in the experimental flow curve.

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Transparency document. Supplementary material

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