Prediction of Stress–Strain Curves of Hot Deformed IF Austenite

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1. Introduction

Prediction of stress–strain, $\sigma \times \varepsilon$, curves under plastic work is of interest and many researchers have dedicated themselves to further improve the capabilities and accuracy of different models.1–9 The proposed models can be of use in FEM codes, for instance, improving prediction performance of loads needed to carry out a given forming process. Constitutive equations for the calculation of $\sigma \times \varepsilon$, curves are also employed in the analysis of load and microstructure evolution in bulk metal forming processes such as hot rolling. Here, industrial schedules can be simulated prior to industrial trials thereby reducing production costs.

Flow behavior varies greatly depending on which type of steel or schedule is in use. A plot of the measured mean flow stress, MFS, versus the inverse of the absolute pass temperature, $1/T$, can be used to identify how the material behaves during deformation in industrial processes.10,11 Conversely, the calculated MFS, evaluated under conditions typically applied to a given mill schedule, can simulate mill logs and render information on how the microstructure of the steel is evolving during production.12,13 This “microstructural engineering”14 is gaining increasingly importance since it opens a window to quantitatively connect mill operational variables to on line assessment of the evolution of the microstructure and, ultimately, to on line prediction of product properties and final shape.

Previous authors1–9 have dedicated their investigation either to improve model performance or to apply these models to predict $\sigma \times \varepsilon$ of C–Mn or microalloyed steels. Furthermore, little attention has been given to the kinetics of dynamic recrystallization which dominates the shape of the flow curve at large strains. In this work, a series of $\sigma \times \varepsilon$ curves for a Ti added IF steel was simulated according to Sellars’ model15 yielding a reasonable fit to the experimental data. The critical strain for the initiation of dynamic recrystallization, DRX, $\varepsilon_c$, an important parameter of this model, was determined from an analysis of the $\theta \times \sigma$ curves since, owing to the very low C content of IF austenite, quenching to obtain the precise values of $\varepsilon_c$ from direct metallography observation was not feasible. The kinetics of DRX was modeled as a function of testing parameters and an equation for volume fraction recrystallized was derived. The modeling presented here gave good fit in the dynamic recovery,DRV, as well as in the DRX part of the curves. The average error between experimental and predicted curves was around 3%, quite acceptable considering the usual errors found between measured and predicted loads in commercial hot deformation processes.

2. Experimental Techniques

Samples for torsion experiments, 15 mm of length and 6.5 mm in diameter, were cut at 1/4 of the thickness of a hot rolled billet of 100 mm$^2$ cross section. The specimens were machined with their axis parallel to the billet rolling direction. The chemical composition of the IF steel employed in this work was 28 ppm C, 38 ppm N, 0.083 Ti, 0.15 Mn, 0.1 Si, 0.013 P, 0.009 S and 0.058 Al, all numbers in weight percent except where stated otherwise.

Torsion experiments were carried out in a computer controlled servo-hydraulic machine equipped with an infrared furnace the samples being deformed in argon atmosphere. Temperature was controlled by a cromel-alumel thermocouple welded at the sample surface. The specimens were preheated at 1 473 K (1 200°C) for 900 s (15 min) and then cooled to testing temperature at a rate of 1 K/s (1°C/s). All samples were kept at test temperature for 180 s (3 min) prior to twisting in order to homogenize their temperatures.

Tests were performed at temperatures of 1 223, 1 273, 1 323 and 1 373 K (950, 1 000, 1 050 and 1 100°C) and strain rates of 0.1, 1, 3 and 10 s$^{-1}$. All samples were deformed to an equivalent true strain of 7, allowing the occurrence of full DRX and the achievement of the steady state in all tests.

The $\sigma \times \varepsilon$ curves were obtained from the torque versus angular displacement in the usual way, the stress being corrected for the variation in radius; an average increase of 0.6 mm for all tests. The stresses were also compensated for adiabatic heating using the following expression assuming that the dependence of stress on temperature and strain rate is given by an hyperbolic sine law, as reported elsewhere16,17

$$\sigma_{corr} = \frac{1}{\alpha} \sinh^{-1}
\left[\sinh(\alpha \sigma) \exp\left(\frac{Q_{def}}{R} \left(\frac{1}{T} - \frac{1}{T_{corr}}\right)^{1/n}\right)\right]
$$

(1)

where, $Q_{def}$ and $n$ are 342±31 kJ/mol and 0.11 respectively, $\alpha$ is assumed as 0.012,16,17 $\sigma$ and $T$ are the stress and temperature measured during test, $\sigma_{corr}$ is the corrected stress for a test performed at a constant temperature $T_{corr}$.

3. Results and Discussion

Figure 1(a) shows some of the $\sigma \times \varepsilon$ curves obtained in this work. Regardless of testing temperature or strain rate, DRX occurred in all experiments. The curves, as far as simulation is concerned, can be divided into two regions: one in which DRX is the sole softening mechanism balancing work hardening and another in which, besides DRX, DRX also acts as the softening mechanism.
3.1. Simulation of the $\sigma \times \varepsilon$ Curves up to the Initiation of DRX

Modeling $\sigma \times \varepsilon$ curves in this recovery region, that is, up to a critical strain for the initiation of DRX, $\varepsilon_c$, can be carried out using

$$\sigma_c = \sigma_0 + D(1 - \exp(-Ce))^p$$ \hspace{1cm} (2)

with

$$D = \sigma_{0s} - \sigma_0$$ \hspace{1cm} (3a)

and

$$C = -\frac{1}{\varepsilon_c} \ln \left[ 1 - \left( \frac{\sigma_c - \sigma_0}{D} \right)^{1/p} \right]$$ \hspace{1cm} (3b)

$$\varepsilon_c = AZ^n$$ \hspace{1cm} (4)

Here $\sigma_c$, $\sigma_0$ and $\sigma_{0s}$ are the calculated, the yield and the extrapolated stresses and $\sigma_c$, the stress at a constant strain, $\varepsilon_c$, taken as 0.05 in this work, $A$, $n'$ and $p$ are experimental constants and $Z$ is the Zener–Hollomon parameter.

The value of $\sigma_0$ was measured directly from the experimental $\sigma \times \varepsilon$ curves. On the other hand, $\sigma_{0s}$ can only be indirectly estimated since DRX intervenes much before the extrapolated stress can be achieved. This is also the case for $\varepsilon_c$ since quenching the high temperature austenite of IF steels so that the precise values of $\varepsilon_c$ could be measured by direct microstructure observation is not feasible. In the present work, the values of $\sigma_{0s}$ and $\sigma_c$ were measured from a $\theta \times \sigma$ curve as shown in Figs. 1(b) and 1(c). Given the value of $\sigma_c$, $\varepsilon_c$ can be read from the appropriate $\sigma \times \varepsilon$ curve.

The dependence of the stress on the temperature and strain rate was assumed to be described by a hyperbolic sine law. Therefore, at a given strain, $\ln(Z) = C_1 \ln(\sinh(\alpha \sigma)) + C_2$ where $C_1$ and $C_2$ are constants determined by the least square method from a versus graph. The values of $C_1$, $C_2$ and $R^2$, the correlation coefficient, are listed in Table 1 for the stresses $\sigma_{0s}$, $\sigma_c$ and $\sigma_{0s}^*$. As expected the regression coefficient is somewhat smaller for $\sigma_0$ than for the other stresses due to the inherent experimental errors associated with the measurement of this value at the beginning of the $\sigma \times \varepsilon$ curves.

The values of $A$ and $n'$ in Eq. (4) can be determined from a plot as shown in Fig. 2(a) displaying a reasonable correlation, $R^2$ equals to 0.965, between $\varepsilon_c$ and $Z$. In this case, $n'$ is 0.12 and $A$ is 0.012s. Finally, the constant $p$ in Eq. (2) was measured as 1.13±0.07. By applying the coefficients here reported to Eqs. (2) to (4), the recovery part of the $\sigma \times \varepsilon$ curves could be simulated as shown in Fig. 2(b).

3.2. Simulation of the $\sigma \times \varepsilon$ Curves after the Initiation of DRX

Modeling the $\sigma \times \varepsilon$ curve after DRX has initiated can be realized by the use of the expression

$$\sigma = \sigma_c - X_{DRI}(\sigma_c - \sigma_0)$$ \hspace{1cm} (5)

Here, as shown in Fig. 3(a), $\sigma_c$ was plotted as a function of $Z$ and the coefficients $C_1$, $C_2$ and $R^2$, similarly to the cases

| Coefficients | $C_1$ | $C_2$ | $R^2$ |
|--------------|-------|-------|-------|
| Stress, MPa  |       |       |       |
| $\sigma_{0s}$| 7.87  | 34.99 | 0.786 |
| $\sigma_c$   | 8.80  | 34.06 | 0.984 |
| $\sigma_{0s}^*$| 4.35  | 28.47 | 0.996 |

Table 1. Values of constants $C_1$ and $C_2$ for the calculation of the stresses $\sigma_{0s}$, $\sigma_c$ and $\sigma_{0s}^*$, $R^2$ is the least square regression coefficient.
The following expression could be derived for the critical strain for the initiation of DRX, ε_c, was measured in this study. The time for 50% of DRX to occur, t_50, could be then directly measured for each test and plotted as a function of test temperature and strain rate from which 

\[
X_{\text{DRX}} = 1 - \exp\left[ -0.693 \left( \frac{\sigma - \varepsilon_c}{\dot{\varepsilon}} \right)^{1.7} \right]
\]

When Eqs. (5) to (7) are applied to strains higher than ε_c, a full σ×ε curve can be simulated as shown for some selected examples in Fig. 4(a). A more complete picture of a comparison between measured and predicted stresses is shown in Fig. 4(b). Here, the measured and predicted curves were compared at strain intervals of 0.1 for all curves obtained in this work. A relative error for all points plotted in this way was calculated by using

\[
\text{Average % error} = \frac{100}{N} \sum_{i=1}^{N} \left( \frac{|\sigma_{\text{measured}} - \sigma_{\text{calculated}}|}{\sigma_{\text{calculated}}} \right)
\]

4. Conclusions

(1) A series of stress strain curves for a Ti added IF steel was simulated according to Sellars’ model yielding a reasonable fit to the experimental data.

(2) The critical strain for the initiation of DRX, ε_c, was determined from an analysis of θ×ε curves and subsequent modeling of the fractional softening by DRX, assumed as proportional to the ratio \((\sigma - \varepsilon_c)/(\sigma - \varepsilon_m)\), gave a reasonable fitting to the curves in the range of strains larger than ε_c.

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