Hot deformation behavior of a medium carbon microalloyed steel

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1. Introduction

Hot forged medium carbon microalloyed steels are appropriate materials for several engineering applications. For example, some automobile components such as connecting rods, crankshafts, and wheel hubs can be manufactured from these steels [1]. In order to improve the properties of this material, the parameters of the forming process must be controlled carefully. The understanding of the microstructural behavior of the steel under consideration is therefore required, together with the constitutive relation describing material flow. Industrial hot deformation processing such as forging for these steels is conducted in the temperature range of stability of austenite phase. Due to low stacking fault energy of austenite, the major restoration process during hot deformation is dynamic recrystallization (DRX). DRX is an important phenomenon for controlling microstructure and mechanical properties in hot working. In some materials such as aluminum, the dynamic recovery (DRV) can balance work hardening, and a plateau in the stress–strain curve is achieved. However, in many materials such as austenite phase in steels, the kinetics of DRV is low, and DRX can initiate at a critical condition of strain accumulation. Due to the great impact of DRX on high temperature flow stress and its effect on the microstructure and properties of the material after processing, the prediction of critical strain and other characteristic points of the flow curve, and determinations of hot flow behavior are quite important in the modeling of industrial hot working processes [2,3]. This paper revisits the results of the study on the hot deformation behavior of a medium carbon microalloyed steel during hot compression test. Moreover, the application of constitutive equations to determine the hot working constants of this material was critically discussed. Since the Zener–Hollomon parameter is extensively used in hot working, calculating the correct value of deformation activation energy (Q) is essential. There are many ways to fit the data for this calculation. Some of them may lead to significant errors, as shown in the present work.

2. Experimental materials and procedures

2.1. Preparation of flow curves

The hot compressed flow curves of a medium carbon microalloyed steel with chemical composition of 0.34 wt% C–1.52 wt% Mn–0.72 wt% Si–0.083 wt% V–0.018 wt% Ti–0.0145 wt% Al–0.0114 wt% N were used in this work. The temperature and strain rate were in the range of 850–1150 °C and 0.0001–3 s\textsuperscript{−1}, respectively. These data were taken from Ref. [1], and collected and revisited here. It must be noted that under all of the testing conditions considered in the present work, dynamic precipitation did not take place. More details of the experiments can be found in Ref. [1]. The elastic portion of flow curves was removed and flow data were fitted and smoothed with a 7th to 9th order polynomial.
2.2. Work hardening rate analyses

The analyses based on work hardening rate ($\dot{\theta}$) were performed to reveal if DRX occurred and also to determine the characteristic points of flow curves. The $\dot{\theta}$ values were obtained using the central difference approach [2] by the following equation:

$$\dot{\theta}_{i} = \frac{\sigma_{i} - \sigma_{i-1}}{\epsilon_{i} - \epsilon_{i-1}}$$  

The onset of DRX was detected from the inflections in plots of the $\dot{\theta}$ versus $\sigma$ or from the minimum in plots of $-d\dot{\theta}/d\sigma$ versus $\sigma$ (before the peak stress for both type of curves) [3,4]. The latter curves were used to detect the critical stress for initiation of DRX ($\sigma_C$). Moreover, the peak ($\sigma_P$) and steady-state ($\sigma_S$) stresses, peak ($\epsilon_P$) and steady-state ($\epsilon_S$) strains, and the critical strain for the onset of DRX ($\epsilon_C$) were detected from the $\dot{\theta}$–$\sigma$ curves, $\dot{\theta}$–$\epsilon$ curves, and inflection points in $\ln \dot{\theta}$–$\epsilon$ plots, respectively. Fig. 1 shows the method used for determination of characteristic points of flow curves by using the work hardening rate. For example, the exact values of peak stress and strain were determined at the first occurrence of $\dot{\theta} = 0$ in the $\dot{\theta}$–$\sigma$ and $\dot{\theta}$–$\epsilon$ curves, respectively.

2.3. Constitutive analyses

Constitutive equations were used to calculate the activation energy and hot deformation constants of this material. The base equation is shown in Eq. (2). In this equation, the Zener–Hollomon parameter ($Z$) is the temperature-compensated strain rate and $Q$ is the activation energy of deformation.

$$Z = \dot{\epsilon} \exp \left( \frac{Q}{RT} \right) = f(\sigma)$$  

As can be seen in this equation, the $Z$ parameter is also considered as a function of stress. The power law description of stress (Eq. (3)) is only suitable for high stresses. However, the hyperbolic sine law (Eq. (5)) can be used for a wide range of temperatures and strain rates.

$$Z = f(\sigma) = A'\sigma^n$$  

$$Z = f(\sigma) = A' \exp(\beta\sigma)$$  

$$Z = f(\sigma) = A[\sinh(\alpha\sigma)]^n$$

where $A', A, n, \alpha, \beta$ and $\alpha(=\beta/n)$ are apparent material constants. The stress multiplier $\alpha$ is an adjustable constant which brings $\alpha\sigma$ into the correct range to make constant $T$ curves in $\ln \dot{\theta}$ versus $\ln(\sinh(\alpha\sigma))$ plots linear and parallel [2,5].

3. Results and discussion

3.1. Stress–strain curves

Flow curves obtained at different temperatures and strain rates are shown in Fig. 2. Most of the curves corresponding to deformation temperatures higher than 850°C exhibit typical DRX behavior with a single peak stress followed by a gradual fall towards a steady state stress. The peak stress becomes less obvious when the strain rate is increased or the deformation temperature is decreased. However, the cyclic or multiple peaks DRX can be observed for high temperatures and low strain rates.

For a number of samples deformed at temperatures higher than 850°C in Fig. 3, the $\dot{\theta}$–$\sigma$ curves show inflection point and the $-d\dot{\theta}/d\sigma$ versus $\sigma$ curves show global minimum, which are considered as signs for the onset of DRX. In each curve of Fig. 3a, $\dot{\theta}$ linearly decreases with the flow stress. After that, the curves gradually change to another linear line and then drop towards $\dot{\theta} = 0$ at peak stress.

At the deformation temperature of 850°C, the shape of flow curves resembles typical dynamic recovery (DRV) behavior. However, inflections in $\dot{\theta}$–$\sigma$ plots are considered as stronger indications of the occurrence of DRX. Therefore, the $\dot{\theta}$–$\sigma$ analysis was performed to reveal if DRX occurred. The $\dot{\theta}$–$\sigma$ curves and corresponding $-d\dot{\theta}/d\sigma$–$\sigma$ curves of one sample at 850°C and the other at 900°C are shown in Fig. 4. For the sample deformed at 850°C, neither an inflection point nor a minimum were determined on the abovementioned curves. Therefore, in this case, only DRV is underway. This behavior is consistent with the results of the previous work [1].
Fig. 2. Flow curves obtained at different deformation conditions.

Fig. 3. Work hardening rate analyses for some deformation conditions.
3.2. Determination of hot working constants

The description of flow stress by Eq. (2) is incomplete, because no strain for determination of flow stress is specified. Therefore, characteristic stresses such as steady state, peak or the one corresponding to a specific strain may be used for this purpose. Since the steady state stress may not be precisely attained or there may be some softening due to morphological evolution, it is usual to use the peak stress [2,6–10]. By substitution of \( f(\dot{\varepsilon}) \) from Eqs. (3)–(5) to Eq. (2) and taking natural logarithm from each side of resulting equations, the following expressions could be derived for the peak stress:

\[
\ln \dot{\varepsilon} + \frac{Q}{R} \left( \frac{1}{T} \right) = \ln A' + n' \ln \sigma_P \tag{6}
\]

\[
\ln \dot{\varepsilon} + \frac{Q}{R} \left( \frac{1}{T} \right) = \ln A'' + \beta \sigma_P \tag{7}
\]

\[
\ln \dot{\varepsilon} + \frac{Q}{R} \left( \frac{1}{T} \right) = \ln A + n \ln \{\sinh(\alpha \sigma_P)\} \tag{8}
\]

At constant deformation temperature, and assuming the activation energy as a constant parameter, partial differentiation of Eqs. (6)–(8) yields to the following equations, respectively:

\[
n' = \left[ \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma_P} \right]_T \tag{9}
\]

\[
\beta = \left[ \frac{\partial \ln \dot{\varepsilon}}{\partial \sigma_P} \right]_T \tag{10}
\]

\[
n = \left[ \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \{\sinh(\alpha \sigma_P)\}} \right]_T \tag{11}
\]

It follows from these expressions that the slope of the plot of \( \ln \dot{\varepsilon} \) against \( \ln \sigma_P \) and the slope of the plot of \( \ln \dot{\varepsilon} \) against \( \sigma_P \) can be used for obtaining the values of \( n' \) and \( \beta \), respectively.

Fig. 4. Work hardening rate analyses for two different deformation conditions.

Fig. 5. Plots used for calculation of hot deformation constants (the peak stress and strain rate values are in MPa and s\(^{-1}\), respectively).
These plots are shown in Fig. 5a and b. In each plot, the lines are essentially parallel, so using Eqs. (6) and (7) in the wide range of deformation conditions, even high and low stresses, is reasonable. The linear regression of these data, results in the average values of 6.617 and 0.099 for $n'$ and $\beta$, respectively. This gives the value of $\sigma = \beta/n' = 0.015$. According to Eq. (11), the slope of the plot of $\ln \varepsilon$ against $\ln \{\sinh(\alpha \sigma_p)\}$ can be used for obtaining the value of $n$ (Fig. 5c). The average value of $n$ was determined as 4.928. The calculated values of hot deformation constants are consistent with the values reported for another medium carbon microalloyed steel [11] and the present steel using a different approach [1].

3.3. Determination of the deformation activation energy

At constant strain rate, partial differentiation of Eqs. (6), (7) and (8) yields to the following equations, respectively:

![Graphs showing plots used for calculation of deformation activation energy and plots used to derive the constitutive equations.](image)

Fig. 6. Plots used for calculation of deformation activation energy (the peak stress and temperature values are in MPa and K, respectively).

Fig. 7. Plots used to derive the constitutive equations (the peak stress values are in MPa).
\[ Q = Rn \left[ \frac{\partial \ln \sigma_P}{\partial (1/T)} \right]_{\varepsilon} \]  
\[ Q = R \beta \left[ \frac{\partial \sigma_P}{\partial (1/T)} \right]_{\varepsilon} \]  
\[ Q = R n \left[ \frac{\partial \ln \sinh(\alpha \sigma_P)}{\partial (1/T)} \right]_{\varepsilon} \]

It follows from these expressions that the slope of the plots of \( \ln \sigma_P, \sigma_P \) or \( \ln \sinh(\alpha \sigma_P) \) against the reciprocal of absolute temperature can be used for obtaining the value of \( Q \). These plots are shown in Fig. 6. The linear regression of these data, results in the average values of 377, 397 and 394 kJ/mol for activation energy form Eqs. (12), (13) and (14), respectively. Analysis of the correlation coefficient \( (R^2) \) of these regression values reveals that the hyperbolic sine equation (Eq. (14)) has better fit to experimental data. Therefore, the apparent activation energy of hot working was considered as 394 kJ/mol.

In many research works, one of the Eqs. (12)–(14) is taken from the literature for calculation of apparent activation energy without any knowledge about their origin, and as shown in the abovementioned analyses, it may lead to significant errors. Moreover, it is usual to take the value of \( \alpha = 0.012 \) for steels, which is an additional source of error for analyses based on hyperbolic sine law (Eq. (14)).

The value of 394 kJ/mol for deformation activation energy deviates largely from the self-diffusion in austenite, which is reported as 270 kJ/mol [1]. Although the hot working activation energy depends on the material being considered, it is usually referred to as apparent value, because no account is generally taken of the internal microstructural state and it is only derived from an Arrhenius plot with a linear range and the assumption that the microstructure remains constant. The hot working activation energy values are often much larger than any imagined atomic mechanism. This can be ascribed to the fact that in hot working the microstructures may initially differ to some degree for different preheats and evolve rapidly at different rates during testing [5]. Moreover, for microalloyed steels, the solute drag effect of microalloying elements prohibits the movement of boundaries and results in a higher activation energy.

3.4. The constitutive equations

According to Eqs. (3)–(5), the plots of \( \ln Z \) versus \( \ln \sigma_P, \sigma_P \) and \( \ln(\sinh(\alpha \sigma_P)) \) may be used to find the relationship between \( Z \) and

![Fig. 8. Characteristic points of flow curves as functions of Z (the stress values are in MPa).](image-url)
methods shown in Fig. 1 and subsequently plotted in Fig. 8 on a logarithmic scale with respect to $Z$. The characteristic points of flow curves were determined by the methods shown in Fig. 1 and subsequently plotted in Fig. 8 on a logarithmic scale with respect to $Z$ using power relations. Regression analysis of these curves resulted in the following equations: 

\[ Z = \dot{\varepsilon} \exp \left( \frac{394 \times 10^3}{RT} \right) = 83.1 \times \sigma_p^{0.678} \]  
\[ (15) \]

\[ Z = \dot{\varepsilon} \exp \left( \frac{394 \times 10^3}{RT} \right) = 8.7 \times 10^{10} \times \exp(0.0972 \times \sigma_p) \]  
\[ (16) \]

\[ Z = \dot{\varepsilon} \exp \left( \frac{394 \times 10^3}{RT} \right) = 3.92 \times 10^{13} \times [\sinh(0.015 \times \sigma_p)]^{0.957} \]  
\[ (17) \]

Amongst these relations, the power (Eq. (15)) and the hyperbolic sine law (Eq. (17)) equations show good fits (Fig. 7). However, there is a possibility of the power law breakdown at high stresses. Therefore, Eq. (17) is more preferable to express hot working characteristics of the investigated alloy.

3.5. Characteristic points of flow curves

The characteristic points of flow curves were determined by the methods shown in Fig. 1 and subsequently plotted in Fig. 8 on a logarithmic scale with respect to $Z$ using power relations. Regression analysis of these curves resulted in the following equations:

\[ \sigma_p = 0.567 \times Z^{0.147} \]  
\[ (18) \]

\[ \dot{\varepsilon}_p = 0.0079 \times Z^{0.1026} \]  
\[ (19) \]

\[ \sigma_C = 0.504 \times Z^{0.147} = 0.89\sigma_p \]  
\[ (20) \]

\[ \dot{\varepsilon}_C = 0.0049 \times Z^{0.1026} = 0.62\dot{\varepsilon}_p \]  
\[ (21) \]

\[ \sigma_S = 0.513 \times Z^{0.147} = 0.90\sigma_p \]  
\[ (22) \]

\[ \dot{\varepsilon}_S = 0.2746 \times Z^{0.0266} \]  
\[ (23) \]

The $Z$ exponent of 0.1026 in Eq. (19) is relatively consistent with the classical literature data which has a value between 0.12 and 0.22. For Nb steel and 17-4 PH stainless steel, the low values of 0.09 and 0.11 have also been reported [4,12]. Moreover, the $Z$ exponent of 0.147 for describing stresses is consistent with previous reports on microalloyed steels [13]. According to Eqs. (20) and (21), the normalized critical stress and strain can be expressed as $\sigma_C/\sigma_p = 0.89$ and $\varepsilon_C/\varepsilon_p = 0.62$, respectively. The nearly similar values for normalized critical stress have been reported for 304 and 17-4 PH stainless steels [3,14]. The value for normalized critical strain is also consistent with the previous studies on steels which has been reported a value in the range of 0.6–0.8. It should be noted that for some steel grades such as AK steel and 17-4 PH stainless steel, the low values of 0.52 and 0.47 have also been reported [3,4].

4. Conclusions

(1) The majority of stress–strain curves of the medium carbon microalloyed steel in the wide range of temperatures and strain rates used in this study, exhibited typical DRX behavior with a single peak stress followed by a gradual fall towards a steady state stress. However, some samples showed typical DRV behavior and some show cyclic DRX behavior.

(2) It was shown that for correct calculation of hot deformation activation energy, one of the three expressions of $Z$, namely the power law, exponential law and hyperbolic sine law, results in the appropriate value. For the experimental alloy, the hyperbolic sine law was found to be the appropriate relation, which resulted to the value of 394 kJ/mol.

(3) The following constitutive equation can be used to express hot working characteristics of the investigated alloy:

\[ Z = \dot{\varepsilon} \exp \left( \frac{394 \times 10^3}{RT} \right) = 3.92 \times 10^{13} \times [\sinh(0.015 \times \sigma_p)]^{0.957} \]

(4) The $Z$ exponent for peak stress and peak strain was determined as 0.147 and 0.1026, respectively.

(5) The normalized critical stress and strain for initiation of DRX were found to be 0.89 and 0.62, respectively.

References