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Preprint

This is the submitted version of a paper published in *Materials Science Forum*.

Citation for the original published paper (version of record):

Safara Nosar, N., Sandberg, F., Engberg, G. (2018)

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Materials Science Forum, 941: 458-467

<https://doi.org/10.4028/www.scientific.net/MSF.941.458>

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N.B. When citing this work, cite the original published paper.

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Characterization of hot deformation behavior in a 13% chromium steel

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Abstract

The behavior of a 13% chromium steel subjected to hot deformation has been studied by performing hot compression tests in the temperature range of 850 to 1200°C and at strain rates from 0.01 to 10 s⁻¹. The uniaxial hot compression tests were performed on a Gleeble thermo-mechanical simulator. The best function that fits the peak stress for the material and its relation to the Zener-Hollomon parameter (Z) is derived. The average activation energy of this alloy for the entire test domain was found to be about 557 [kJmol⁻¹] and the dynamic recrystallization (DRX) kinetics was studied to find the fraction DRX during deformation.

Keywords: 13% chromium steel; hot deformation; Zener-Hollomon parameter; Dynamic recrystallization Kinetic.

Introduction

Dynamic recrystallization (DRX) is an important parameter for modeling of hot working. The onset of DRX is known to happen at a critical stress (σ_c) and strain (ϵ_c) [1]. Although during deformation stress increases continuously after initiation of DRX, the material starts to soften and strain hardening counterbalances with the softening due to DRX at some point, i.e. the strain hardening rate (θ) becomes zero. Stress and strain corresponding to this point are known as peak stress (σ_p) and peak strain (ϵ_p). In some circumstances, at stress-strain curves of constant strain rate, stress will decrease after the peak stress and reach a plateau after the so-called steady-state stress and strain (σ_s , ϵ_s). However, DRX might happen without any obvious peak in the flow stress curves as well [2].

In order to model the material behavior during hot deformation, it is important to know the values of critical, peak and steady-state stress (strain). Except in the case of a visible peak in the flow curve which is usually promoted by high temperatures and low strain rates, direct measurement of peak stress and its associated strain is difficult and it is even more complicated in case of finding the critical stress and strain. Poliak and Jonas [2,3] introduced a method to find these values from experimental stress-strain data which is going to be employed in this work to relate them with the Zener-Hollomon parameter (Z) and DRX kinetics.

Experimental

The material used in this investigation is a martensitic stainless steel with a chemical composition of C 0.68, Mn 0.7, Si 0.4, P (max) 0.025, S (max) 0.01, Cr 13, and Fe balance wt%. Cylindrical specimens of diameter 10 [mm] and height of 15 [mm] were machined out of the as-received hot worked billets. Prior to compression, all the specimens were reheated to 1250°C and held for nearly two minutes before cooling down to the deformation temperature. After soaking of 15 seconds at the test temperature, the uniaxial hot compression tests were carried out on a Gleeble thermo-mechanical simulator in the temperature range of 850 to 1200°C and nominal strain rates of 0.01 to 10 s⁻¹ at an interval of one order of magnitude.

Results and Discussion

Flow stress

An appropriate polynomial curve is fitted to the experimental data points of this alloy at all deformation conditions. Fig. 1 demonstrates the fitted curves to the experimental true stress-strain data for all strain rates at the deformation temperature of 1100°C.

Fig. 1. Effect of strain rate on the flow curves of the samples deformed at 1100°C. Polynomials fitted to the experimental data are shown with dashed lines.

Some curves exhibit the typical form of the DRX flow curves with a single peak in the flow curve followed by softening towards a steady state plateau. This form becomes less recognizable when the deformation temperature drops or the strain rate increases.

Kinetic Analysis

The prerequisite for studying the Zener-Hollomon parameter and DRX kinetics is to identify the characteristic points of the flow curve including critical, peak and steady-state stresses and strains. According to Poliak and Jonas [2,3], σ_p and σ_c can be obtained by plotting the work hardening rate versus true stress. True stress at the point where the work hardening rate reach zero corresponds to the peak stress and the inflection point on the curve corresponds to the critical stress. Steady-state stress in this work is assumed to be attained when the work hardening rate becomes zero for the second time in the work hardening rate versus true strain plot [4]. All the characteristic points are extracted by applying the mentioned method to these plots as illustrated in Fig. 2 for deformation temperature of 1200°C and strain rate of 0.01 [s⁻¹].

Fig. 2. Work hardening rate versus true stress (a) and true plastic strain (b) for temperature of 1200 °C and strain rate of 0.01 [s⁻¹].

In order to investigate the effect of temperature and strain rate during hot deformation, a standard kinetic equation using the well-known Zener-Hollomon parameter (Z) is defined and mathematically expressed as:

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right). \quad (1)$$

In Eq. 1, $\dot{\epsilon}$ denotes the strain rate [s⁻¹], Q is the activation energy of deformation [kJmol⁻¹], R is the universal gas constant having the value of 8.3145 [Jmol⁻¹K⁻¹], and T is the absolute temperature [K].

Sellars et al. [5] suggested a hyperbolic sine function to relate the Zener-Hollomon parameter and the flow stress during hot working condition according to Eq. 2.

$$Z = A [\sinh(\alpha \sigma_p)]^n. \quad (2)$$

Here A , α , and n are material constants and σ_p denotes the peak stress during the deformation. Combining Eq. 1 and Eq. 2, applying logarithm to both sides of the equations and rearranging it will give Eq. 3, which can be used to extract the unknown material constants.

$$\log(\dot{\epsilon}) = \left[\log A - \frac{Q}{RT \ln(10)} \right] + n \log(\sinh(\alpha \sigma_p)). \quad (3)$$

Knowing the value of peak stress for all deformation conditions, the variation of the logarithm of peak stress with the logarithm of strain rate according to Eq. 3 is depicted in Fig. 3.

Fig. 3. Plot of hyperbolic sine function of peak stress with strain rate at different temperatures for determining material parameters n and α .

Material parameters n and α are calculated from the linear regression of the experimental data in a way that the difference between the slope of the lines was minimum for all temperatures and the linear fit with experimental points have the best fit possible (highest R square value). The obtained values for this alloy are 4.586 and 0.001073 respectively.

In order to find other unknowns, namely A and Q , it is possible to rearrange Eq. 3 and apply natural logarithm to get Eq. 4 as below:

$$\ln(\dot{\epsilon}) - n \ln(\sinh(\alpha \sigma_p)) = \ln(A) - \frac{Q}{R} \frac{1}{T}. \quad (4)$$

Knowing n and α , it is possible to plot the data according to Eq. 4 and find A and Q . Fig. 4 shows the linear regression of the experimental data for different strain rates and temperatures where Q is calculated from the mean slope of the lines and A is determined from the average value of the intersection points of the lines with the vertical axis.

Fig. 4. Variation of the inverse of temperature with the intercept of strain rate and hyperbolic sine function of peak stress at different strain rates and temperatures for determining the deformation activation energy (Q) and constant A .

Having all the necessary unknowns, the Zener-Hollomon relation for the studied steel of this work can be represented by the following equation:

$$Z = \dot{\epsilon} \exp\left(\frac{577600}{RT}\right) = 5.13 \times 10^{21} [\sinh(0.01073 \sigma_p)]^{4.586}. \quad (5)$$

The resulting n and α values are consistent with the reported values of $n = 4.9$ and $\alpha = 0.011$ for a similar alloy [6]. On the other hand, the activation energy (Q) is found to be considerably higher than the reported values of 448 [6] and 413 [KJmol⁻¹] [7]. This could be the result of the difference in carbon content in the alloys, which is more than one order of magnitude higher in the investigated alloy of the present work. Higher carbon content will cause higher solid solution hardening in the alloy and higher Q .

Fig. 5 shows how the experimental points of peak stress were acceptably fit the defined hyperbolic sine function at different deformation conditions.

Fig. 5. The relation between $\ln(\sinh(\alpha\sigma_p))$ and $\ln(Z)$ and the best linear fit.

A simpler dependence between peak, critical and steady-state stress and the Z parameters can be acquired by plotting them against natural logarithm of Z, as in Fig. 6.

Fig. 6. Regression analysis of critical, peak, and steady-state (SS) stress and Zener-Hollomon parameter and best linear fits.

From the linear regression analysis, the coefficients of the relations can be found and they can be expressed as below:

$$\sigma_p = 13.68 \ln(Z) - 557.15 \quad (6)$$

$$\sigma_c = 12.88 \ln(Z) - 523.35 \quad (7)$$

$$\sigma_s = 13.38 \ln(Z) - 548.5 \quad (8)$$

Dynamic Recrystallization (DRX) Kinetics

DRX is an important softening mechanism but generally, it is difficult to determine the fraction recrystallized (X_{DRX}) experimentally and it needs tedious microstructure observation. The DRX fraction is reported to be derived from two different methods having the flow curves characteristic points. In the first method [4,8], it is enough to know the peak and steady-state stress from the deformation data according to Eq. 9 where σ is the instantaneous true stress.

$$X1_{DRX} = \frac{\sigma_p - \sigma}{\sigma_p - \sigma_s} \quad (9)$$

The second method [7–9] has a classical JMAK-type relation and uses the critical and peak strains to calculate the DRX fraction, see Eq. 10.

$$X2_{DRX} = 1 - \exp\left(-k \left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_p}\right)^\alpha\right). \quad (10)$$

Here ε is the true plastic strain and k and α are constants which are defined to be 0.693 and 2, respectively [7,9]. In this study, ε_c is replaced with ε_p [8] since the flow softening practically starts at peak strain although it is known that DRX initiates at the critical strain. Therefore Eq. 10 can be transformed into its new form as follows:

$$X2_{DRX} = 1 - \exp\left(-0.693 \left(\frac{\varepsilon - \varepsilon_p}{\varepsilon_p}\right)^2\right). \quad (11)$$

Applying Eq. 9 and 11 to the experimental data of present work, the fraction of DRX can be calculated for different deformation temperatures and strain rates. Fig. 7 shows the place of peak and steady state stress on the flow curve and the resulting DRX fraction from both methods for the deformation temperature of 1000°C and strain rate of 0.01 [s⁻¹] together with the corresponding strain hardening curve for comparison.

Fig. 7. The true stress-strain curve at 1000 °C and strain rate of 0.01 s⁻¹ where σ_p and σ_s are pointed out (a), and DRX fraction calculated from both methods (Eq. 9 and 11) and their relation with strain hardening (b).

Predicted DRX fraction from both methods show very good agreement with each other and the DRX fraction increases after strain hardening becomes zero for the first time (ϵ_p) and reaches unity when the work hardening equals zero for the second time, i.e. steady-state strain (ϵ_s).

Based on Eq. 11, the DRX fraction at different deformation condition can be calculated and Fig. 8 shows the fraction DRX at various deformation temperatures and strain rates of 0.01 to 1 [s⁻¹].

Fig. 8. Predicted results of DRX volume fraction from method 2 (Eq. 11) for all temperatures and strain rates of 0.01 to 1 [s⁻¹]. The first number in the legends shows deformation temperature, the second part is the strain rate, and the last number is ln(Z) for the respective deformation condition.

As can be seen in the Fig. 8, the DRX kinetics is generally faster for lower Z values, i.e. higher temperatures and lower strain rates and as it was expected for the temperature of 850⁰C and strain rates of more than 0.01 [s⁻¹] the DRX fraction is almost zero. Finally, it should be noted that Z is not the sole governing parameter in DRX kinetics since other parameters, e.g. initial grain size of the material, are also effective.

Conclusions

The hot deformation behavior of a 13% chromium martensitic stainless steel has been investigated using a Gleeble thermo-mechanical simulator in a wide range of temperatures (850-1200⁰C) and strain rates (0.01-10 [s⁻¹]).

- A constitutive equation of the flow stress for this alloy was developed and the deformation activation energy (Q) was about 577 [kJmol⁻¹].
- The characteristic points of the flow curves and their relation with Z were found.
- The steady-state stress and peak stress (strain) were used to predict the kinetics of DRX.
- The DRX kinetic model for this alloy was formulated with a classical JMAK-type relation of: $X_{DRX} = 1 - \exp(-0.693 (\frac{\epsilon - \epsilon_p}{\epsilon_p})^2)$.

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