Materials Research Express

PAPER

Critical condition parameters and kinetics of dynamic recrystallization for hot deformed 1 wt%Cr-1 wt%Mo rotor steel

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Keywords: steel, hot deformation, dynamic recrystallization, strain hardening rate, critical stress, Avrami equation

Abstract

Isothermal hot compression tests of low alloy 1 wt%Cr–1 wt%Mo medium carbon rotor steel were carried out over the temperature range from 850 °C–1050 °C under three strain rates (\(\dot{\varepsilon}\)) varying from 0.001 s\(^{-1}\)–0.1 s\(^{-1}\). The hot deformation behavior, activation energy and material constants were determined by constitutive analysis. Onset of critical condition parameters for dynamic recrystallization (DRX) of the present steel were determined with the help of mathematical models developed by Poliak and Jonas. DRX kinetics were studied to determine the fraction of dynamic recrystallization with the help of Avrami type model. Also, the values of Avrami power exponent (\(n\)) and material constant (\(K\)) were calculated for Avrami equation in each deformation condition. Optical and scanning electron (SEM) micrographs of the as-received and the deformed specimens were analyzed to understand the flow stress behavior of this steel.

1. Introduction

1 wt%Cr–1 wt%Mo steel is widely used as rotor of steam power generation plant [1]. This steel exhibits better combination of strength and ductility at highly stressed industrial (creep, fatigue and high temperature etc) environment. To avoid failure at highly stressed conditions, their mechanical and microstructural properties play an important role. These properties mainly depend on its manufacturing processes and conditions. In other words, these mechanical and microstructural properties are controlled by the term called dynamic recrystallization (DRX) [2, 3]. In the recent years, prediction of initiation of DRX is of major interest for forging processes in industries. Many researchers have proposed different mathematical and computational methods for the determination of initiation of DRX [4]. For initiation of DRX, Ryan and McQueen in 1990 [5] proposed that it can be determined by deflection in the slope of strain hardening rate with stress curves. Flow curves which attain single or multi peak stress followed by softening and steady state stress, show dynamic recrystallization [6]. Also, the initiation of DRX always occurs before the flow stress peak (\(\sigma_f\)) as discussed by M J Luton and sellers in 1969 [7]. Stress and strain corresponding to initiation point of DRX in flow stress curves represent critical stress (\(\sigma_c\)) and critical strain (\(\varepsilon_c\)) respectively [8–10]. Based on thermodynamics of irreversible process, Jonas and Poliak [11, 12] developed an alternative method to determine critical condition for initiation of DRX. According to them, strain hardening rate (\(\dot{\theta} = \frac{d\varepsilon}{d\sigma}\)) curve is plotted up to \(\dot{\theta} = 0\) with respect to flow stress. Inflection in this curve represents onset of DRX. According to Najafizadeh and Jonas [13] strain hardening rate versus flow stress i.e. \(\dot{\theta}\) versus \(\sigma\) curve was again fitted into 3rd order polynomial. This Polynomial expression was differentiated with respect to flow stress. The minimum point in \(\frac{d\dot{\theta}}{d\sigma}\) versus \(\sigma\) plot represents critical stress of dynamic recrystallization. Texture and microstructural evaluations are governed by DRX which determine final property of metals and alloys. The kinetics of DRX is crucial to understand in different hot compression conditions, for achieving desirable microstructure and property [14]. Researchers have used Avrami equation to understand the DRX kinetics of different materials at different deformation conditions [10, 14, 15] as given below.

\[
X = 1 - \exp (-K \{f(\varepsilon)\})^n.
\]
Where \( X \) indicates volume fraction of DRX, \( f(\varepsilon) \) is the term depending on strain, \( n \) and \( K \) are Avrami power exponent and material constant.

Aim of the present study is to determine critical conditions of onset of dynamic recrystallization and the volume fraction of dynamic recrystallization with the help of Avrami type model at different deformation conditions. Apart from that, this study is also helpful to determine hot deformation behavior and deformation activation energy of 1 wt%Cr–1 wt%Mo rotor steel.

2. Experimental details

In this study 1 wt%Cr–1 wt%Mo low alloy medium carbon rotor steel is used. Chemical composition of this steel is determined by Emission Optical Spectrometer (Thermo Jarrell Ash Model No.-13160901).

Before compression test, dilatometry test was conducted to determine critical temperatures of present steel with the help of CCT dilatometer with LVDT in thermomechanical simulator (Gleeble 3800®). For this test, cylindrical steel specimen of 10 mm diameter and 70 mm length was heated up to 1100 °C with the heating rate of 5 °C s\(^{-1}\). After 5 min of soaking time, heated specimen was cooled to room temperature with cooling rate of 1 °C s\(^{-1}\). After the dilatometry test all the critical temperatures were noted down from the dilation versus temperature graph. Based on the dilatometry test results, uniaxial compression tests were carried out in Gleeble 3800®. Cylindrical specimens of 10 mm diameter and 15 mm length were used for compression tests. In this test specimens were heated up to austenitic temperature i.e. 1100 °C with heating rate of 5 °C s\(^{-1}\). after soaking time of 5 min, heated specimens were cooled to different deformation temperatures (850 °C, 950 °C & 1050 °C) with cooling rate of 1 °C s\(^{-1}\). with varying strain rate from 0.001 s\(^{-1}\)–0.1 s\(^{-1}\) up to 0.69 true strain followed by water quenching as shown in figure 1.

After the compression test, specimens were prepared for microstructural studies. Specimens were cut from center and parallel to the compression axis. All the specimens were polished according to standard metallographic practice i.e. by paper polishing up to 4/0 emery paper followed by cloth polishing. Cloth polishing was done by alumina water suspension. Vilella etchant was used for etching the specimens [16].

3. Results and discussion

3.1. Determination of inter critical temperature region

Dilation versus temperature graph (figure 2) shows dilation increases sharply with increase in temperature with heating rate of 5 °C s\(^{-1}\) up to 780 °C. This is simply due to thermal expansion. It then starts decreasing with further increasing temperature up to 856 °C. This decrease in the dilation is due to start of formation of austenite which has closed packed crystal structure. After this dilation again increases and temperature reaches up to 1100 °C. After soaking time of 5 min at 1100 °C, it is cooled to room temperature with cooling rate of 1 °C s\(^{-1}\).
Further, figure 2 shows contraction taking place from temperature range \(1100 ^\circ C - 660 ^\circ C\) and then dilation taking place. This dilation is attributed to formation of ferrite which has bcc structure (not close packed). \(A_\text{f}\) temperature was noted down. During heating and cooling \(A_\text{C}_1\), \(A_\text{C}_3\), \(A_\text{r}_1\) and \(A_\text{r}_3\) were found to be \(780 ^\circ C\), \(856 ^\circ C\), \(660 ^\circ C\) and \(510 ^\circ C\) respectively. On the basis of dilatometry test results, hot compression tests were carried out in single phase austenitic region.

### 3.2. Flow stress curves analysis

Figure 3 shows nature of flow stress curves obtained by deformation of 1 wt%Cr–1 wt%Mo medium carbon low alloy steel specimens at different deformation conditions. Deformation at strain rate of 0.001 s\(^{-1}\) with varying temperature range from \(850 ^\circ C\)–\(1050 ^\circ C\) indicates that with increasing deformation temperature, flow stress decreases. Moreover, all the true stress - true strain curves in figure 3(a) show peak stress followed by softening in flow curves, indicating DRX. Additionally it is also observed that peak strain and peak stress values increase with decrease in deformation temperature at constant strain rate. Deformation at 0.01 s\(^{-1}\) strain rate with temperatures at \(950 ^\circ C\) and \(1050 ^\circ C\) show peak in flow curves followed by softening indicating occurrence of DRX. Moreover, no sharp stress peak was observed after deformation at \(850 ^\circ C\) with same strain rate. The true stress- true strain curve obtained from this deformation condition indicates the nature of deformation is dynamic recovery (DRV) type as shown in figure 3(b). In figure 3(c) it is seen that deformation at 0.1 s\(^{-1}\), both flow curves exhibit sharp peak stress followed by softening and steady state stress, except deformation at \(850 ^\circ C\), flow stress curve shows work hardening [17] in nature. From given plots in figure 3, it is also observed that at constant deformation temperature with increasing strain rate the values of flow stress, peak stress and peak strain increases and vice-versa. Dotted lines show adiabatic temperature rise in true stress – true strain curves during deformation. In this study, corrected stress data (due to adiabatic heating) is used to analyze constitutive equation.

### 3.3. Constitutive equation analysis

Constitutive equation was used to analyze plastic flow behavior of hot deformed steels, which could be expressed in terms of Arrhenius equation [9, 18]. In the present work, this equation was used to identify hot deformation activation energy and material constants from 0.05–0.69 true strain of hot deformed metal. Arrhenius equation is used to analyze relationship among high temperature deformation with applied flow stress and strain rate. Although, flow stress behavior of hot deforming metals depends on strain rate and temperature, which could be expressed by Zener–Hollomon parameter [9, 19]. In these equations (2)–(4), \(\sigma\) is flow stress from 0.05–0.69 true strain at the interval of 0.05, \(Z\) is called temperature compensated strain rate [19] or Zener–Hollomon parameter and \(Q\) is called hot deformation activation energy (kJ mole\(^{-1}\)).

\[
Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = C \sigma^{n_\sigma} \alpha < 0.8
\]  \hspace{1cm} (2)

\[
Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = B \exp(\beta \sigma) \alpha > 1.2
\]  \hspace{1cm} (3)
Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right) = A \sinh \left( \alpha \sigma \right)^n \quad \text{For all } \sigma \quad (4)

Where \( C, B, A, n, n', \alpha \) and \( \beta \) are material constants, \( T \) is Temperature in kelvin. \( \alpha \) is adjustable constant [20] and is given as,

\[ \alpha \approx \beta / (n') \quad (5) \]

This stress multiplier \( \alpha \) brings \( \alpha \sigma \) value in correct range to attain the values of deformation activation energy and material constant \( n \). Equation (2) is power law expression showing hot deformation behavior for low stress value, similarly equation (3) applicable for deformation at high stress value. Equation (4) is Sine hyperbolic equation, applicable for all stress values. It is also called the term ‘universal constitutive equation’ [21].

3.4. Determination of material constants and activation energy

After considering adiabatic temperature rise and correction in flow stress from the data obtained by hot deformation, the material constants and apparent activation energy are determined.

At constant deformation temperature, material constants \( \beta, n' \) and \( n \) are determined by average slopes of flow stress \( \sigma \), \( \ln(\sigma) \) and \( \ln(\sinh(\alpha \sigma)) \) with respect to \( \ln(\dot{\varepsilon}) \) respectively. Graphical method for finding the value of material constants \( n \) and apparent activation energy \( Q \) by average slopes of \( \ln(\sinh(\alpha \sigma)) \) with respect to \( \ln(\dot{\varepsilon}) \) at constant temperature (figure 4(a)) and \( 1/T \) at constant strain rate deformation as shown in figure 4(b) respectively.

At 0.55 true strain, the values of \( \beta, n', \alpha, n \) and apparent activation energy were calculated as 0.062, 7.05, 0.0153, 3.51 and 456.42 kJ mol\(^{-1}\) respectively.

Intercept of linear fitting curve between \( \ln(Z) \) versus \( \ln(\sinh(\alpha \sigma)) \) at 0.55 true strain exhibits the value of \( \ln(A) \) is equals to 36.49. Value of material constant \( A \) is found to be 7.05 \( \times \) 10\(^{15}\).

By putting the values of material constants and activation energy in equation (4), Zener–Hollomon parameter can be expressed in terms of flow stress \( \sigma \) and strain rate \( \dot{\varepsilon} \) as shown in equation (6). Deformation at 0.001 s\(^{-1}\)–0.1 s\(^{-1}\) with varying temperature range from 850 °C to 1050 °C at 0.55 true strain, the deformation behavior of 1 wt%Cr-1 wt%Mo medium carbon low alloy steel can now be expressed as,

\[ \text{Figure 3. True stress-true strain curves at different hot deformation conditions for steel specimens.} \]
These values of material constants and activation energy are closer to the reported values of similar kind of hot deformed steels \[22–24\]. Due to the effect of alloying elements, the apparent activation energy for hot deformation (456.42 kJmol\(^{-1}\)) of present steel is much larger than the self-diffusion activation energy of austenitic steel i.e. 312 kJmol\(^{-1}\) \[25, 26\].

3.5. Prediction of flow stress
In this study the material constants and activation energy are calculated for the strains ranging from 0.05 true strain to 0.69 true strain with the interval of 0.05 by the same method as discussed in section 3.4.

All the material constants were plotted as a function of true strain and fitted with a 5th order polynomial as shown in figure 5. From figures 5(a)–(d) the variation of \(a\), \(\ln A\) and \(Q\) decrease with increasing strain up to 0.25 true strain and then increase with increasing strain, except material constant \(n\) are in decreasing manner with increasing strain as shown in figure 5(b).

By solving equation (4), the constitutive equation can be written as shown below,

\[
\left(\frac{Z}{A}\right)^{\frac{1}{n}} = \sinh (\alpha \sigma) = \frac{e^{\alpha \sigma} - e^{-\alpha \sigma}}{2}.
\]

(7)

Again, \(e^{\alpha \sigma} = \left(\frac{Z}{A}\right)^{\frac{1}{n}} + \left(\frac{Z}{A}\right)^{\frac{1}{n}} + 1\)^{\frac{1}{n}}.

(8)

By taking logarithm both side of the equation (8), the equation (9) can be written as,

\[
\sigma = \frac{1}{\alpha} \ln \left(\frac{Z}{A}\right)^{\frac{1}{n}} + \left(\frac{Z}{A}\right)^{\frac{1}{n}} + 1\right)^{\frac{1}{n}}.
\]

(9)

The above constitutive equation represents the predicted flow stress in terms of \(Z\) (Zener-Hollomon parameter). The prediction of flow stress can be obtained by putting the values of material constants in equation (9), which is obtained by 5th order polynomial functions with respect to strain (figure 5). In this study, the prediction of flow stress is obtained for each deformation condition with the strain ranging from 0.05–0.69 true strain at the interval of 0.05.

3.6. Validation of developed constitutive equation
For the verification of determined constitutive equation, the true stress–true strain curves in figures 6(a)–(c) show the comparison between predicted flow stresses and experimental flow stresses at each deformation condition. The dotted and solid line curve shows predicted flow stress and experiments flow stress (based on adiabatic temperature correction). Also, figure 6(d) shows the linear fitting of predicted flow stress data with respect to experimental flow stress data is close to 1 i.e. correlation coefficient value (R\(^2\)) is about 0.98. It
represents that the developed constitutive equation shows very good predictability of flow stress with experimental flow stress data.

### 3.7. Critical conditions for DRX

A mathematical method for determination of onset of DRX was developed by Poliak and Jonas \[11, 12\] and later on Najafizadeh and Jonas have simplified this method to obtain critical condition for DRX \[13, 27\]. From figure 3 elastic portion of curves were removed and fitted with 9th order polynomial function up to the 0.69 true strain. Each 9th order polynomial expression was differentiated with respect to strain to obtained strain hardening rate $q_s^e_\theta = \frac{d\sigma}{de}$.

From $\theta - \sigma$ plots in figure 7, it is seen that strain hardening rate decreases with increasing stress. $\theta$ curve touches $\theta = 0$ line, called peak stress ($\sigma_p$). In the above plots, some deflections are observed before reaching the peak stress. These deflections are called as inflection point or critical stress ($\sigma_c$) for onset of dynamic recrystallization. It occurs before the peak stress. The strain corresponding to critical stress is called critical strain $\varepsilon_c$ \[10, 11, 21\]. Critical stress could be clearly identified by 3rd order polynomial fit of $\theta$ curve up to the peak stress followed by differentiating the polynomial Eqn. with respect to stress \[13, 27\] as shown in figure 8.

Each minimum point of $\left(-\frac{d\theta}{d\varepsilon}\right)$ curve in above plots shows critical stress for dynamic recrystallization at each deformation condition. No minimum points were found in deformation conditions at 0.01 s$^{-1}$ & 0.1 s$^{-1}$ for 850 °C temperature, showing DRV and strain hardening nature in flow stress curves. From figures 7 and 8, deformations at constant temperature, it is clear that peak stress as well as critical stress increase with increasing strain rate. Additionally, at lower strain rate deformation conditions, $\sigma_s$, $\sigma_p$, $\varepsilon_c$ and $\varepsilon_p$ decrease with increasing deformation temperature.

Linear fitting of peak stress with respect to critical stress as well as peak strain with respect to critical strain are shown in figure 9. Values of $\sigma_s$, $\sigma_p$, $\varepsilon_c$ and $\varepsilon_p$ increase with increase in strain rate at constant deformation temperature and vice versa. The correlation coefficient ($R^2$) values were determined as approx. 0.98 & 0.96 respectively.

In different deformation conditions, critical condition parameters for DRX of the present steel vary in terms of $Z$ – parameter as shown in figure 10. It can be observed that $\sigma_s$, $\sigma_p$, $\varepsilon_c$ and $\varepsilon_p$ increase with increasing...
Z - parameter. The ratio of $\sigma_c / \sigma_p$ & $\varepsilon_c / \varepsilon_p$ were found to be approx. 0.89 & 0.40 respectively. The critical ratio of this steel is also compared with similar kind of steels. The critical ratio may also depend on temperature, strain rate and compositional of materials \[18\]. The $\sigma_c / \sigma_p$ ratio of present steel is approximately similar to the $\sigma_c / \sigma_p$ ratio of medium carbon micro alloy steel and low carbon micro alloy steel i.e. 0.89 and 0.9 respectively \[10, 29\]. The $\varepsilon_c / \varepsilon_p$ ratio of present steel is calculated as 0.4 which is smaller than medium carbon micro alloy steel and low carbon micro alloy steel i.e. 0.6 and 0.64 \[10, 29\].

3.8. Kinetics of DRX

Equation (10) is the Avrami model, used to determine static recrystallization \[14\].

$$X = 1 - \exp(-Kt^n).$$

(10)

Where $X$ and $t$ are a fraction of DRX and transformation time for DRX, $K$ and $n$ are material constants.

Later on, the modified form of equation (10) is used to study dynamic recrystallization kinetics, based on the time required for 50 % recrystallization ($t_{50}$) as shown below \[14\],

$$X = 1 - \exp \left\{ -K \left( \frac{t}{t_{50}} \right)^n \right\}. $$

(11)

The fraction of dynamic recrystallization can be easily determined by flow stress curves compared to microstructural evaluation. The expression can be expressed as given below \[30–32\],

$$\sigma - \sigma_p = X_{DRX} (\sigma_p - \sigma_i) $$

(12)

Where $\sigma_p$ and $\sigma_i$ are peak and steady state stress, $X_{DRX}$ stands for fraction of dynamic recrystallization. From equation (11), time from the initiation of dynamic recrystallization is replaced by strain $\left( \frac{\varepsilon - \varepsilon_c}{\varepsilon_p} \right)$ at constant strain rate deformation, so the dynamic recrystallization in terms of volume fraction can be expressed with the expression of modified Avrami type model, as given below \[14, 15\].
Where $X_{\text{DRX}}$, $n$ and $K$ stand for volume of fraction in dynamic recrystallization, Avrami power exponent and constant. $\varepsilon$, $\varepsilon_c$ and $\varepsilon_p$ are true strain, critical strain and peak strain respectively.
By rearranging and taking natural logarithm on both sides of equation (13), gives,

\[ \ln \left( 1 - X_{\text{DRX}} \right) = - K \left( \frac{\varepsilon - \varepsilon_c}{\varepsilon_p} \right)^n \]  

(14)

Again rearranging and taking natural logarithm on both sides of equation (14), it is written as:

\[ \ln \left\{ \ln \left( \frac{1}{1 - X_{\text{DRX}}} \right) \right\} = \ln K + n \ln \left( \frac{\varepsilon - \varepsilon_c}{\varepsilon_p} \right) \]  

(15)
By linear fitting of data points obtained from \( \frac{\ln \left( \frac{1}{1 - \lambda_{\text{DRX}}} \right)}{\ln \left( \frac{\varepsilon - \varepsilon_p}{\varepsilon_p} \right)} \) versus \( \ln \left( \frac{\sigma - \sigma_p}{\sigma_p} \right) \) plot exhibits the values of \( n \) and \( K \) at different deformation conditions. Under the deformation at 0.001 \( s^{-1} \) with temperature of 1050 °C, the value of \( n \) and \( K \) was determined to be 8.40 and 0.0125 respectively from figure 11.

Table 3, shows the values of \( n \) and \( K \) at different deformation temperature for Avrami type model.

| Temperature (°C) | Strain rate (s\(^{-1}\)) | \( n \) | \( K \) |
|-----------------|--------------------------|-----|-----|
| 850             | 0.001                    | 4.6 | 0.115 |
| 950             | 0.001                    | 5.4 | 0.093 |
| 1050            | 0.001                    | 8.4 | 0.012 |
| 950             | 0.01                     | 7.1 | 0.113 |
| 1050            | 0.01                     | 3.36| 0.135 |
| 950             | 0.1                      | 2.07| 0.669 |
| 1050            | 0.1                      | 4.69| 0.075 |

By substituting the average value of \( n \) and \( K \) in equation (13) [31], the kinetic model of dynamic recrystallization is given below,
\[ X_{\text{DRX}} = 1 - \exp \left\{ -0.173 \left( \frac{\varepsilon - \varepsilon_c}{\varepsilon_p} \right)^{3.08} \right\} \quad (16) \]

Where \(\varepsilon\), \(\varepsilon_c\) and \(\varepsilon_p\) are true strain, critical strain and peak strain respectively and they are different for different deformation conditions. Equation (16) is used for the graphical representation of volume fraction of dynamic recrystallization with respect to true strain. Figures 12 and 13 represent the graphical representation for the variation of volume fraction of dynamic recrystallization \(X_{\text{DRX}}\) and strain hardening rate \((\theta)\) with respect to true strain at different deformation conditions.
Under the deformation at 1050 °C over the strain rate range of 0.001 s\(^{-1}\)–0.1 s\(^{-1}\), strain hardening rate versus true strain plots are shown in figure 12(a). All curves are in decreasing manner with increasing strain and cross the line where strain hardening rate is zero. Moreover, with further increasing strain the curves again reach to the \(q = 0\) line, and complete one cycle of DRX, which show deformations are DRX type. From equation (16), the fraction of DRX are calculated at these deformation conditions. The volume fractions of recrystallization of metal were plotted with respect to true strain as shown in figure 12(b). In the above plot, it is observed that with increasing strain, volume fraction of DRX curve reaches to 1 in each deformation condition, which shows that it is fully recrystallized. Additionally, it can be also concluded that to obtain equal amount of recrystallization fraction, more strain is needed at constant deformation temperature with increasing strain rate.

The plot in figure 13(a), shows variation of \(q\) with respect to true strain under the deformation at strain rate of 0.01 s\(^{-1}\) with varying temperatures from 850 °C–1050 °C. In the above deformation conditions only deformation at 850 °C, strain hardening curve just touches the \(q = 0\) line (without crossing), shows DRV in nature. Additionally, remaining two \(q\) curves complete one cycle of DRX with increasing strain. From equation(16), the fraction of DRX are calculated at these deformation conditions.
(16), volume fractions of DRX curves have been plotted with respect to strain (figure 13(b)). In this plot, it is seen that larger strain is needed to reach same amount of recrystallization fraction at constant strain rate with decreasing deformation temperature.

3.9. Microstructural analysis

Microstructures of as received and various hot deformed specimens are shown in figure 14. Optical and SEM (scanning electron microscopy) micrographs are shown in figures 14(a)–(f) and (g–l) respectively.

It is observed that as-received steel specimen consists of ferrite and bainite, figures 14(a) and (g). The uniform carbide distribution (white spots) can be identified in SEM micrograph figure 14(g). All hot deformed specimens at various strain rates and temperatures as mentioned in figure 14 are recrystallized microstructure except deformation at 850°C–0.1 s⁻¹ specimen. No carbide precipitates are visible in any hot deformed microstructures. These microstructures consist of predominantly martensite along with small amount of bainite. The reason for the formation of martensite is that, they are all water quenched specimens from hot deformed temperatures i.e. 850 °C, 950 °C and 1050 °C. Small amount of retained austenite could be there.
Grain growth has been observed in the microstructure 1050 °C–0.001 s⁻¹ and it has been highlighted in figures 14(f) and (l). Strain localization can be seen in specimen 850 °C–0.1 s⁻¹ (figures (b) and (h)) shown by arrow. No strain localization has been observed in other hot deformed condition.

4. Conclusions

In present study, hot deformation behavior and determination of critical conditions for dynamic recrystallization of 1 wt%Cr–1wt%Mo rotor steel was studied. The followings are the conclusions of the present study:

(A) Constitutive equation for present steel was developed for the deformation at strain rates 0.001 s⁻¹–0.1 s⁻¹ with varying temperatures from 850 °C–1050 °C. Also, the apparent activation energy for hot deformation was calculated as about 456.42 kJ.

(B) Z-Parameter of the present steel in terms of strain rate and flow stress is given below

\[ Z = \varepsilon \exp \left( \frac{456.422 \times 10^3}{RT} \right) = 7.05 \times 10^{15} [\sinh (0.015 + \sigma)]^{0.51}. \]

(C) It is observed that deformation at 0.001 s⁻¹ with varying temperatures ranging from 850 °C – 1050 °C and also deformation at strain rate of 0.01 s⁻¹ & 0.1 s⁻¹ with temperatures at 950 °C & 1050 °C show DRX in nature.

(D) Linear fitting of predicted flow stress data and experimental flow stress data is close to 1 i.e. correlation coefficient value (R²) is about 0.98. It represents that the developed constitutive equation shows very good predictability of flow stress with experimental flow stress data.

(E) The correlation coefficient (R²) values for linear fitting of peak stress with respect to critical stress and linear fitting of peak strain with respect to critical strain are determined as approx. 0.98 & 0.96 respectively.

(F) The variation of critical condition parameters have been shown and the ratios of \( \sigma_C / \sigma_p \) & \( \varepsilon_C / \varepsilon_p \) are found to be approx. 0.89 & 0.40 respectively.

(G) The values of \( n \) & \( K \) were determined for the determination of volume fraction of DRX with the help of Avrami model at different deformation conditions.

Acknowledgments

The authors would like to acknowledge Bharat Heavy Electricals Limited for the rotor steel, Metallurgical and Materials Engineering Department, Institute Instrumentation Centre, Indian Institute of Technology Roorkee for experimental support and FIST DST New Delhi for providing Gleeble 3800.

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