A modified kinetics model and softening behavior for static recrystallization of 12Cr ultra-super-critical rotor steel

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Abstract

In this paper, the static recrystallization (SRX) of 12Cr ultra-super-critical (USC) rotor steel was investigated by a series of hot compression tests on a Gleeble1500D thermal simulator. Double-hit hot deformation tests were conducted at temperatures of 1223K–1323 K and strain rates of 0.001 s$^{-1}$–0.1 s$^{-1}$ with inter-pass times of 10s–180 s. A conventional kinetics model of SRX was established based on flow curves obtained by regression analysis under different deformation conditions. However, a significant deviation resulted between predicted and experimental values for the SRX fraction, and therefore a modified kinetics equation was proposed by analysing the SRX characteristics and possession of the capability to accurately predict SRX softening behaviour was confirmed. Effects of hot deformation parameters on SRX softening behaviour and SRX grain size were discussed. Furthermore, microstructure deforming was observed at different inter-pass times with an optical microscope (OM), electron backscatter diffraction (EBSD) and transmission electron microscope (TEM). Analysis showed that recovery was the main softening mechanism and the fundamental nucleation mechanism for SRX was bulging at the grain boundary.

1. Introduction

Due to sound obdurability, corrosion resistance, creep resistance and oxidation resistance, 12Cr USC rotor steel has been used extensively in high and medium pressure steam turbine components [1–4]. Prior reports on high-Cr USC rotor steel focused on the composition design and optimization, while only a few articles were related to its hot deformation behaviour, especially softening process during the hot deformation [5–9]. The softening process, including recovery and recrystallization, is used to balance the work hardening during the hot deformation process [10]. The dynamic recrystallization (DRX) will occur when the strain and stress exceed their respective critical values, and the metadynamic recrystallization (MDRX) will occur in the DRX microstructure during the inter-pass times. When the strain and stress is less than the critical values of DRX, static recovery (SRV) or even SRX will occur during the subsequent heat preservation or cooling process [11, 12]. Multi-pass processing is very common in hot deformation, in which static softening between passes plays an important role, as this affects the forming load of each pass and the degree of microstructure evolution [13–19]. Due to the SRX is one of the most important metallurgical events governing the flow strength and the resulting microstructure, this paper focused on the SRX behaviour of the steel. To optimise hot forming processing parameters and make an appropriate processing path for the tested steel, understanding the kinetics behaviour and softening mechanism of SRX was vital.

SRX kinetics behaviour of different materials has been widely studied. Chastukhin et al [20] discovered that the SRX kinetics of niobium-microalloyed pipe steels depended on the chemical composition. Andrade et al [21] provided the percentage of softening versus delay time curves and discussed the retarding effect of the addition of molybdenum, niobium and vanadium on the rate of static recovery and recrystallization. Lin et al [22, 23] proposed kinetic equations and a grain size model to predict SRX behaviours of hot deformed 42CrMo steel. Xia et al [24] developed SRX kinetics equations and reported on the influences of different parameters on the recrystallization behaviour of 34CrNiMo steel. Gutierrez et al [25] studied the SRX kinetics of a commercial...
Table 1. Chemical composition of 12Cr USC rotor steel (wt%).

|      | C     | Si   | Mn   | Cr   | Ni   | Mo   | P     | S     |
|------|-------|------|------|------|------|------|-------|-------|
| W    | 0.11−0.12 | <0.12 | 0.40−0.60 | 10−12 | 0.70−0.90 | 1.0−1.1 | <0.01 | <0.008 |
| V    | 0.60−0.90 | 0.15−0.30 | <0.01 | 0.04−0.06 | Bal |

purity aluminium alloy and highlighted the variation of $t_{0.5}$ under different conditions. Li et al. [26] determined the macrotextures and microstructures of a magnesium alloy AZ31 during SRX. Kuger et al. [27] used a cellular automata model to investigate the influence of initial microstructure topology on SRX kinetics and referred to the dependence of mean grain size on initial grain topology. Su et al. [28] discussed SRX kinetics behaviour. Li et al. [29] compared the SRX kinetics of Cold-Rolled Mg-3Al-1Zn alloy stimulated by electropulse treatment and conventional heat treatment via EBSD analysis technology.

Although numerous studies have explored the SRX behaviour for different materials, most of these have only investigated the softening rule at different deformation parameters, including deformation temperature, prestrain, strain rate and initial grain size, and lacked microstructure analysis. Few studies have addressed the microstructure to explore the static softening and SRX nucleation mechanisms of 12Cr USC rotor steel during the inter-pass time. Generally, nucleation mechanisms of SRX include the mechanism of growth and nucleation of subgrain (subgrain merging nucleation and subgrain boundary moving nucleation) and the protruding nucleation mechanism of grain boundary [30, 31].

In this research, the SRX behaviour of 12Cr USC rotor steel during hot deformation was systematically investigated by double-hit hot compression experiments. A modified kinetics model of SRX was established and the predicted capacity for the SRX fraction was verified. The effects of deformation parameters including temperature, strain rate, prestrain and initial austenite grain size on SRX softening behaviour and SRX grain size were analysed. Moreover, the softening and SRX nucleation mechanisms within the inter-pass time were investigated by OM, EBSD and TEM.

2. Experimental procedures

The chemical composition (wt%) of 12Cr USC rotor steel is given in table 1. The double-hit hot compression experiments were carried out on a Gleeble 1500D thermo-simulation machine. Due to we have investigated the single pass hot compression behavior of the studied material [3], and obtained the conditions for DRX to occur. In order to only SRV or SRX to occur during the inter-pass time, DRX must not occur [12]. Therefore, the deformation temperatures were selected as 1223 K, 1273 K and 1323 K, strain rates were determined as 0.001 s\(^{-1}\), 0.01 s\(^{-1}\) and 0.1 s\(^{-1}\) and the inter-pass times were set as 10 s, 30 s, 60 s and 180 s. At the above condition, the prestrains were determined as 0.1, 0.15 and 0.2. Of course, it should be kept the deformation was interrupted below the critical strain required for DRX. In order to study the effects of temperature, prestrain, strain rates and inter-pass times, the material was annealed during heat treatment at 1423 K for 8 h to ensure homogenisation. The microstructures after annealing were observed by means of EBSD, as shown in figure 1. Before the EBSD observation, mechanical polishing and electro-polishing were performed on the sample surface so as to acquire a strain-free surface. Then the EBSD studies were conducted using a Zeiss Supra 55VP microscope operating at 20 kV with a scan speed of 160.70 Hz. Maps of the Vickers grid were created with a step size of 1.2 μm with a confidence indexes value higher than 90%. Experimental specimens with a gauge length of 12 mm and diameter of 8 mm were cut from the studied steel. Then, all specimens were austenitised at 1473 K for 2 min to obtain the initial grain size of 160 μm, and the hot compression experiments were performed according to the schematic representation shown in figure 2(a). Once the double-hit compression was completed, specimens were immediately water-quenched to retain the high temperature microstructure observed using OM, TEM and EBSD.

To investigate the effect of initial austenite grain size on microstructural evolution during SRX, the tested steel was annealed at 1473 K for 5 h, 1473 K for 8 h, and at 1423 K for 8 h, then some specimens were heated to 1473 K for 2 min to obtain the initial grain sizes (curve 2 in figure 2(b)). The initial grain sizes, measured by using a linear intercept method on OM, was approximately 121 μm, 187 μm and 160 μm, respectively. The other specimens were compressed to study the effect of initial grain sizes on the SRX behavior (curve 1 in figure 2(b)).
3. Results and discussion

3.1. Quantifying the SRX fraction and double-hit flow curves

3.1.1. Quantifying the SRX fraction

Based on the principle that yield stress at high temperature is a sensitive measure of structural change, many offset-stress methods including 0.2%, 2% and 5% offset yield strength have been proposed to calculate the softening fraction resulting from SRX [32–34]. Li et al. [33] found that the fractional softening calculated using an offset of 0.2% was approximately the same as that determined from the mean flow stress method. By contrast, softening measured using the present 2% offset approach was consistently lower than that calculated using either the 0.2% offset or mean flow stress technique. The 2% offset method was concluded to be particularly well suited for following the progress of recrystallization alone. Cho et al. [14] pointed out that the 2% offset method avoided the noise that sometimes appeared in the early part of experimental high temperature flow curves. In this way, the calculations of fractional softening became more reliable. In this paper, the 2% offset yield stress was used to quantitatively calculate the SRX fraction based on the characteristics of 12Cr USC rotor steel and the associated experimental parameters of SRX (figure 3). The SRX fraction was obtained using equation (1) [14, 34],

$$X_S = \frac{\sigma_m - \sigma_1}{\sigma_m - \sigma_2}$$

where $X_S$ was the SRX fraction; $\sigma_m$ was the maximum stress of the first pass; and $\sigma_1$ and $\sigma_2$ represented the offset stress (2%) during the first and second hits.

3.1.2. Double-hit flow curves

Typical double-hit compression stress-strain curves of 12Cr USC rotor steel deformed at different deformation conditions are presented in figure 4. In figure 4(a), the value of $\sigma_2$ decreased significantly with the increase of deformation temperature at the same deformation conditions. This could be attributed to the fact that the increase of deformation temperature accelerated the rate of grain boundary migration, that further promoted the occurrence of SRX. Distinction of the occurrence of softening was difficult when the inter-pass time was
short, while $\sigma_2$ decreased with extension of the inter-pass time at definite deformation temperature, prestrain, initial grain size and strain rate (figure 4(b)). This behavior demonstrated that the inter-pass time strongly affected the static softening fraction [29]. SRX is a thermal activation process and strongly dependent on atomic diffusion, and therefore the increase of inter-pass time permits a longer time for diffusion of atoms, promoting the occurrence of SRX [30]. Figure 4(c) shows the double-hit stress-strain curve of the test steel at 1323 K with strain rates of 0.001 s$^{-1}$, 0.01 s$^{-1}$ and 0.1 s$^{-1}$, respectively. The degree of softening of SRX decreased with the

Figure 3. Schematic representation of the 2% compensation method.

Figure 4. Typical stress-strain curves of the double-hit hot compression tests under different conditions (a) temperature; (b) inter-pass time; (c) strain rate; and (d) prestrain.
decrease of the strain rate at the same inter-pass time (figure 4(c)). Figure 4(d) shows the influence of the first pass deformation on the flow curves in the second pass at the temperature of 1323 K and the strain rate of 0.1 s$^{-1}$. It can be seen from figure 4(d) that the softening increased with an increase in prestrain.

3.2. Kinetics model of SRX

The kinetics model of SRX could be described using an Avrami-type equation [equation (2)] [35, 36],

$$ X_S = 1 - \exp \left[ -0.693 \left( \frac{t}{t_{0.5}} \right)^n \right] $$

where $X_S$ was the fraction of SRX; $n$ was the material constant; and $t_{0.5}$ represented the time for 50% softening by SRX, which could be expressed as equation (3),

$$ t_{0.5} = B \hat{\varepsilon}^{b_1} \varepsilon^{b_2} d_0^{b_3} \exp \left( \frac{Q_S}{RT} \right) $$

where $B$, $b_1$, $b_2$, and $b_3$ were material constants; $\hat{\varepsilon}$ was the strain rate, $R$ represented the gas constant (J/mol K); $T$ referred to the absolute temperature (K); and $Q_S$ was the SRX activation energy (kJ/mol).

Taking the natural logarithm on both sides of equations (2) and (3), the material constants could be determined through equations (4) and (5) respectively,

$$ \ln \left[ \ln \left( \frac{1}{1 - X_S} \right) \right] = \ln 0.693 + n \ln \left( \frac{t}{t_{0.5}} \right) $$

$$ \ln t_{0.5} = \ln B + b_1 \ln \hat{\varepsilon} + b_2 \ln \varepsilon + b_3 \ln d_0 + \frac{Q_S}{RT} $$

According to equation (4), the constant $n$ could be obtained from the ln(ln(1/(1-X))) versus ln t curves (figure 5). In these curves, the value of constant $n$ was obtained from the mean slope of these fitting lines as 0.638. Based on equation (5), the relationships between $\ln t_{0.5}$ and $\ln \hat{\varepsilon}$, $\ln \varepsilon$, $\ln d_0$, and 1000/T could be determined. Using linear regression analysis, the values of $B$, $b_1$, $b_2$, $b_3$, and $Q_S$ were obtained as 1.82*10^-9, -0.468, -2.476, 0.92 and 155423.99 J mol$^{-1}$, respectively. Therefore the kinetics model of SRX could be described using the
In order to verify the kinetics model of SRX behavior, the values of the SRX softening fraction predicted using the kinetic equation (6) and the ones calculated from experimental data, are compared under different conditions (shown in figure 6). In most cases, there was a large deviation between the predicted and experimental values, illustrating that the conventional Avrami equation could not accurately predict the SRX behaviour of 12Cr USC rotor steel under the given experimental conditions. The reason for this phenomenon was that the value of \( n \) in equation (2) varied with deformation temperature, strain rate, prestrain and initial grain size, resulting in the deviation between experimental and predicted values [37]. Considering that the material parameter \( n \) was not considered a constant, a modified kinetics model of SRX needed to be proposed for 12Cr USC rotor steel.

### 3.3. Modified Avrami kinetics model

In the modified Avrami kinetics model, the material parameter \( n \) was regarded as a variable parameter (marked as \( n_1 \)) calculated by equation (7) [37],

\[
n_1 = C_0^{n_1}e^{C_1d_0^{C_2}}\exp\left(\frac{Q_n}{RT}\right)
\]

where \( C, C_1, C_2, C_3 \) and \( Q_n \) represented material constants. The values of \( n_1 \) are the slopes of the linear regression curves in figure 5. Substituting the values of \( n_1 \) and the corresponding strain rate, strain, initial grain size and temperature into equation (7), the values of \( C, C_1, C_2, C_3 \) and \( Q_n \) can be determined by fitting the relative linear regression curves of \( \ln n_1 \) versus \( \ln \varepsilon \), \( \ln n_1 \) versus \( \ln \varepsilon \), \( \ln n_1 \) versus \( \ln d_0 \), and \( \ln n_1 \) versus \( 1000/T \). The material parameter \( n_1 \) would subsequently be expressed by equation (8),

\[
X_s = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^{0.638}\right] \\
t_{0.5} = 1.82\times10^{-9}\varepsilon^{-0.468}e^{-2.476d_0^{0.92}}\exp\left(\frac{155423.99}{RT}\right)
\]
Based on the calculation process outlined in section 3.2, values of $B$, $b_1$, $b_2$, $b_3$, and $Q_6$ were $7.217 \times 10^{-18}$, $-0.347$, $2.346$, $0.488$ and $397101.78$ J mol$^{-1}$, respectively. Therefore the values of $t_{0.5}$ under various deformation conditions could be derived as equation (9),

$$t_{0.5} = 7.217 \times 10^{-18} \varepsilon^{-0.347} d_0^{0.488} \exp \left(\frac{397101.78}{RT}\right)$$

(9)

Figure 7. Comparisons between predicted and experimental values for $X_6$.

Figure 8. (a) Correlation between experimental and predicted SRX fraction; and (b) Error distribution of experimental and predicted softening fractions.
Consequently, the modified Avrami kinetics model of SRX for 12Cr USC rotor steel was expressed as equation (10),

\[
\begin{align*}
X_S &= 1 - \exp \left[ -0.693 \left( \frac{t}{t_{0.5}} \right)^{b} \right] \\
n_i &= 239.67 \varepsilon^{-0.015} \alpha^{0.09} d_0^{0.24} \exp \left( -\frac{76073.1}{RT} \right) \\
t_{0.5} &= 7.217 \times 10^{18} \varepsilon^{-0.347} \alpha^{-2.346} d_0^{0.488} \exp \left( \frac{397101.78}{RT} \right)
\end{align*}
\]

SRX fractions predicted by equation (10) and experimental values at different deformation conditions were compared to verify the accuracy of the modified Avrami kinetics model (figure 7). Predicted values were in line with experimental values, indicating that the modified kinetics model could accurately predict the SRX behaviour of 12Cr USC rotor steel. Accuracy of the modified model was further verified by calculating the correlation coefficient (R), average absolute relative error (AARE) and root mean square error (RMSE). These parameters were defined by equations (11), (12) and (13) [38],

\[
R = \frac{\sum_{i=1}^{N} (X^{ei}_i - \bar{X}^{p}_i)(X^{p}_i - \bar{X}^{p})}{\sqrt{\sum_{i=1}^{N} (X^{ei}_i - \bar{X}^{p}_i)^2 \sum_{i=1}^{N} (X^{p}_i - \bar{X}^{p})^2}}
\]

\[
AARE(\%) = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{X^{p}_i - X^{ei}_i}{X^{p}_i} \right| \times 100\%
\]

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X^{ei}_i - X^{p}_i)^2}
\]

where N was the total number of data points, \(X^{ei}_i\) was the experimental value, \(X^{p}_i\) referred to the predicted values, and \(\bar{X}^{p}\) and \(\bar{X}^{p}_i\) represented the mean values of \(X^{p}\) and \(X^{p}_i\), respectively.
The correlation coefficient ($R$), average absolute relative error (AARE) and root mean square error (RMSE) values (figure 8(a)) were 0.998, 4.38% and 0.0127, respectively. The error distribution between experimental and predicted values obeyed Gauss distribution concentrating in the range of $-0.01-0.01$ and the mean value of error was 0.003 (figure 8(b)). As such, the modified Avrami kinetics model was further confirmed to be able to predict the SRX softening behaviour of 12Cr USC rotor steel.

3.4. Influences of deformation parameters on the SRX

3.4.1. Effect of temperature

The influence of deformation temperatures (1223 K, 1273 K, 1323 K) was investigated with initial grain size of 160 $\mu$m and strain rate of 0.1 s$^{-1}$. Figure 9(a) illustrates the variation curves of the softening fraction with inter-pass time at different deformation temperatures, which is obvious that the softening fraction increases with increasing deformation temperature. For example, when the inter-pass time is 180 s, the volume fraction of SRX rises from 17.2% to 49.8% by increasing the deformation temperature from 1223 K to 1323 K. This phenomenon agrees well with those reported by Zhou et al [34], Chen et al [36] and Mao et al [39]. Figures 9(b)–(d) shows the optical microstructure under three different deformation temperatures which are deformed at strain rate of 0.1 s$^{-1}$, initial grain size of 160 $\mu$m and inter-pass time of 60 s. The average recrystallized grain sizes were measured as 45 $\mu$m, 52 $\mu$m and 57 $\mu$m for the forming temperatures of 1223 K, 1273 K and 1323 K, respectively. Obviously, the effect of deformation temperature on the SRX grain size ($D_{SRX}$) is significant, and the $D_{SRX}$ increases with increasing forming temperature. The following reasons can account for the above phenomenon. Firstly, due to the softening mechanisms are thermal activation, higher temperature is conducive to the mobility of the recrystallization grain boundaries. Therefore, the effect of temperature on softening is significant [34, 40]. In addition, the $D_{SRX}$ mainly depends on nucleation rate ($N_e$) and grain growth velocity ($G_v$) [36, 40]. The higher temperature will affect the $N_e$ and $G_v$. However, the increase of $G_v$ is much greater, which leads to increase in the value of $G_v/N_e$. Therefore, the $D_{SRX}$ increases with increasing forming temperature.

![Figure 10](image.png)

Figure 10. (a) Effect of strain rate on SRX fraction and deformed microstructures at different strain rates (b) 0.001 s$^{-1}$, (c) 0.01 s$^{-1}$ and (d) 0.1 s$^{-1}$.
3.4.2. Effect of strain rate

Figure 10(a) shows the effect of strain rate on SRX fractions at a temperature of 1323 K and initial grain size of 160 μm. It can be found that an increase in the strain rate leads to an acceleration of the softening kinetics (figure 10(a)). In figures 10(b)–(d), the microstructure deformed at different strain rates (0.001 s⁻¹, 0.01 s⁻¹, 0.1 s⁻¹) with an inter-pass time of 60 s can be observed, and the $D_{SRX}$ were measured as 76 μm, 64 μm, and 57 μm for strain rates of 0.001 s⁻¹, 0.01 s⁻¹ and 0.1 s⁻¹, respectively. It is obvious that the $D_{SRX}$ decreases with increasing strain rate at a given inter-pass time. This phenomenon results from the fact that the higher strain rate is conducive to the dislocation generation rate, the increase of dislocation density and nucleation sites in the deformed microstructure [26, 27]. Additionally, much deformation energy stored in the deformation block under high strain rate conditions, meaning that more substructures can be generated in the initial grains when strain rate is higher, which will lead to more nuclei per unit volume of the grains. Finally, the increase of $N_r$ is much greater than $G_v$, which leads to decrease in the value of $G_v/N_r$. As a result, the grain sizes under higher strain rate are finer than those under lower strain rate.

3.4.3. Effect of prestrain

The static softening curves were plotted against the inter-pass time for three different prestrains (0.1, 0.15, 0.2) at deformation temperature of 1223 K, strain rate of 0.1 s⁻¹ and initial grain size of 160 μm, as shown in figure 11(a). It is obvious that the softening fraction increases with an increase in prestrain at a given inter-pass time. For the prestrain of 0.1, 0.15 and 0.2 and inter-pass time of 30 s, the volume fraction of SRX are 10.5%, 13.3% and 17.9%, respectively. Figures 11(b)–(d) shows the microstructure deformed at different prestrains with an inter-pass time of 30 s, which can be seen that the grain size gradually decreased with increasing prestrain. Grain sizes at different prestrains of 0.1, 0.15 and 0.2 measured by the intercept method were 73 μm, 65 μm and 53 μm, respectively. With the increase in prestrain, the dislocation generation rate, the dislocation density, and deformation energy stored in the deformed block all increases [12, 22, 23, 34, 36]. Therefore, the recrystallized grains nucleate more easily at a higher prestrain, which will results in the increase rate of $N_r$, greater than $G_v$. As a result, the grains become finer when the deformation degree is larger in this study.
3.4.4. Effect of initial grain size

In order to investigate the influence of initial grain size, the specimens are deformed with different initial austenitic grain sizes (121 μm, 160 μm, 187 μm) under the prestrain of 0.1, deformation temperature of 1323 K and strain rate of 0.1 s⁻¹ in this section. In figure 12(a), it can be observed that the initial grain size has little effect on the softening fractions of SRX. At an inter-pass time of 180 s, the initial grain sizes are 121 μm, 160 μm and 187 μm corresponding to the SRX fractions of 50.5%, 49.8% and 47.9%, respectively. Showing that the initial grain size is not the main factor affecting the softening behaviour of SRX. The microstructure deformed at different initial grain sizes with the inter-pass time of 60 s is shown figures 12(b)–(d). The average grain sizes were measured as 55 μm, 57 μm, and 61 μm for initial grain sizes of 121 μm, 160 μm and 187 μm, respectively. Obviously, the effect of initial austenitic grain sizes on the microstructural evolutions during SRX in hot deformed 12Cr USC rotor steel is also not remarkable. Lin et al [23] reported the similar results in 42CrMo steel.

![Figure 12.](image)

3.5. SRX softening mechanism during inter-pass time

Figures 13(a)–(d) presents the typical microstructures deformed at deformation temperature of 1273 K, strain rate of 0.1 s⁻¹ and prestrain of 0.1 with different inter-pass times of 10 s, 30 s, 60 s and 180 s. The OM observation shows that distinct structural changes occurred depending on the inter-pass time and the red arrow represents the nucleation position of recrystallization. After being deformed and held for 10 s, the microstructure is changed from equiaxed grain structure to fibrous structure mixed with elongated grain boundaries along the deformation direction, as shown in figure 13(a). Meanwhile, some austenite grain boundaries begin to arch outward, driven by stored energy and evolved into the new recrystallized grains [red arrow in figure 13(a)]. It indicates that the characteristic of nucleation mechanisms is mainly the bulging at the grain boundary. In figure 13(b), recrystallised small grains are observed in the triangle grain boundary when the inter-pass time is 30 s. With the increase of inter-pass time, more and more recrystallised grains appears along the original grain boundary and begin to grow into the crystal (figures 13(c) and (d)). Especially, when the inter-pass time is up to 180 s, it can be seen in figure 13(d) that the original austenite grains are replaced by uniformly recrystallized fine grains. The above phenomenon results from the fact that the SRX is the thermal activation process related with atomic diffusion. Under the same heat treatment history and deformation schedule, the
atomic diffusion time is longer with the increase of time, and the SRX becomes more sufficient with the increase of time [36].

In this part, the typical microstructures, deformed at different inter-pass times of 10 s and 180 s and the same parameters of deformation temperature of 1273 K, initial grain size of 160 μm, strain rate of 0.1 s⁻¹ and prestrain of 0.1, were analysed by EBSD technology. The grains and subgrains with different orientations are shown with dissimilar colours in figures 14(a)–(b). When the inter-pass time is 10 s, the original grains are elongated along the deformation direction, and some fine recrystallized nuclei are distributed along the original grain boundaries (figure 14(a)). At an inter-pass time of 180 s, the original elongated grains are replaced by recrystallized grains (figure 14(b)). Figure 15 shows the statistical result of misorientation distribution with a range of 2°–60° at the inter-pass times for 10 s and 180 s after compression. Regardless of whether the inter-pass time is 10 s or 180 s, an important feature in figure 15 is that the fraction of high angle boundaries (15°–60°)
appear greater, but the low angle boundaries are still dominated. It indicates that recovery is the main softening mechanism, followed by recrystallization during the inter-pass time studied in this paper. In addition, the inter-pass time of 180 s has higher large-angle boundaries than that of 10 s, which is further proved that the recrystallization occurs under this pass interval condition [31].

TEM observations were used to further explore the nucleation mechanism of 12Cr USC rotor steel during the inter-pass time. Figure 16 shows the microstructure deformed at a deformation temperature of 1323 K, strain rate of 0.1 s$^{-1}$ and prestrain of 0.1 with an inter-pass time of 10 s. In figure 16, the microstructure presents the parallel laths, and some laths emerges the zigzag structure, proving that the nucleation mechanism of the tested steel is mainly due to the bulging at the grain boundary during an inter-pass time of hot deformation. The OM observation shows in figure 13(a) also clarify this nucleation mechanism. The possibility of recrystallization through this mechanism depends on the distance between carbide particles and dislocation density in martensite [41, 42]. Due to the studied steel in this paper belongs to the low carbon steel, dislocation density of martensite played an important role. TEM images of 12Cr USC rotor steel after holding at the forming temperature of 1273 K, strain rate of 0.1 s$^{-1}$ for 30 s and 180 s are shown in figure 17. At the inter-pass time of 30 s, the most remarkable feature of the microstructure is the high dislocation density and the interior of the lath shows the tangle of high dislocation density (figure 17(a)). In figure 17(b), it can be observed that the dislocation density of 180 s is less than that of 30 s and the zigzag structures still exists. In addition, some of the original lath martensites have been interrupted in figure 17(b), suggesting a trace of subgrain coalescence during static softening. Therefore, it can be concluded that the bulging at the grain boundary is the fundamental nucleation mechanism for recrystallization, and the formation and transformation of the subgrain may appear during the inter-pass time of hot deformation for 12Cr USC rotor steel.
4. Conclusions

In this study, the static recrystallization behaviour of 12Cr USC rotor steel was investigated at temperatures of 1223 K, 1273 K and 1323 K, and strain rates of 0.001 s\(^{-1}\), 0.01 s\(^{-1}\) and 0.1 s\(^{-1}\) with recrystallization inter-pass times of 10 s, 30 s, 60 s and 180 s using two-step hot compression experiments. Important conclusions can be summarised as follows:

(1) Stress-strain curves for the tested steel can be obtained under the above mentioned test conditions. According to SRX characteristics, a modified Avrami model is proposed to predict the softening behaviour of SRX for the steel. The activation energy of SRX in the double-hit hot compression of 12Cr USC rotor steel is 397101.78 J mol\(^{-1}\) and the modified kinetics model of SRX can be expressed as follow:

\[
\begin{align*}
X_S &= 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^{n_1}\right] \\
n_1 &= 239.67\varepsilon^{-0.015}d_0^{0.24}\exp\left(\frac{-76073.1}{RT}\right) \\
t_{0.5} &= 7.217 \times 10^{-18}\varepsilon^{-0.347}d_0^{2.346}\exp\left(\frac{397101.78}{RT}\right)
\end{align*}
\]

(2) The effect of deformation parameters on softening fraction and SRX grain size is discussed in detail. The softening fraction is shown to increase with an increase in deformation temperature, prestrain, inter-pass time and strain rate. In addition, the SRX grain size increases with increasing the deformation temperature and decreases with increasing the prestrain and strain rate. However, the initial grain size has little effect on the softening fraction and SRX grain size.

(3) Microstructure that deformed at different inter-pass times is observed by OM, EBSD and TEM. Results showed that recovery is the main softening mechanism and the governing nucleation mechanism of SRX is bulging at grain boundary within the inter-pass time given in this paper.

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Figure 17. TEM images of 12Cr USC rotor steel after holding at 1273 K for (a) 30 s and (b) 180 s.
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