A study on the static recrystallization behavior of an ultrahigh-strength stainless steel

Xiao-hui Wang, Zhen-bao Liu, Jian-xiong Liang, Zhi-yong Yang, Yong-qing Sun, Chang-jun Wang and Yue Qi

1 Institute for Special Steel Institute, Central Iron and Steel Research Institute, Beijing 100081, People’s Republic of China
2 Technical Center of Fushun Special Steel Shares Co. Ltd, Fushun 113006, People’s Republic of China
* Author to whom any correspondence should be addressed.

E-mail: liuzhenbao@nercast.com

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Abstract

The static recrystallization (SRX) behavior of an ultrahigh-strength stainless steel (UHSSS) was investigated via double-hit isothermal compression tests. The results revealed that the kinetics of static recrystallization and the corresponding microstructural evolution were not only prominently influenced by the deformation parameters and initial microstructures but also suppressed due to the precipitation of M₆C carbides below 1050 °C, which sufficiently pinned the boundaries. Numerical models for predicting the recrystallized fraction and grain sizes were proposed based on the experimental results. The kinetics model could predict the process of SRX in the deformation temperature range from 1050 °C to 1150 °C well, whereas there were some deviations between the predictions and experimental results due to the interaction of the M₆C carbides and SRX when the deformation temperature was below 1050 °C.

1. Introduction

The pursuit of light weight, high strength and toughness as well as long service life is a continuous subject in aviation material development, and ultrahigh-strength stainless steel (UHSSS), which exhibits excellent comprehensive mechanical properties and corrosion resistance, was developed against this background. Compared with ultrahigh strength steel, such as 300M and AerMet100, UHSSS exhibits comparable mechanical properties but possesses superior service safety and longer service life and thus has great potential application in aircraft, particularly in landing gear [1]. Generally, the manufacturing process of UHSSS consists of several deformation passes to achieve fine microstructures; dynamic recrystallization usually occurs during hot deformation process such as hot forging and rolling, and the as-cast microstructure is refined. [2, 3]. However, the inhomogeneous strain and temperature fields usually lead to incomplete DRX. Thus, the microstructure of the steels may change during the following heat treatment process because static recovery (SRV), static recrystallization (SRX) [4–6] and metadynamic recrystallization (MDRX) [7–9] usually occur. SRX occurs when the applied strain is lower than the threshold value of DRX. Furthermore, the grain size is significantly refined as SRX proceeds. In general, the microstructural evolution behavior is almost fixed by the given thermomechanical parameters, which has a strong influence on the mechanical properties of steel. Therefore, it is necessary to clarify the influence of the thermomechanical parameters, namely, the deformation temperature (T), true strain (ε) and strain rate (ε), on the SRX behavior during the following heat treatment process. The effects of the deformation parameters on the SRX behavior of steels have been studied by many researchers and study groups utilizing the method of double-hit isothermal compression experiments. For instance, Zhou et al [10] and Liu et al [11] studied the SRX behavior of 25CrMo4 mirror plate steel and 300M steel, respectively, and proposed kinetics models of SRX by considering the influence of T, ε and ε as well as the initial grain size (d₀). In addition, the SRX mechanism of 300M steel was explored by Zhao et al [12], who revealed that static recrystallized grains originally nucleated and germinated at the initial austenite grain boundaries, revealing that the main SRX
mechanism of 300M steel was strain-induced boundary migration. Furthermore, the influence of precipitates on SRX was studied by Wu et al.\cite{13}, who found that the pinning force originating from the precipitates was comparable to the grain migration driving force for SRX in a V-alloyed weathering steel, which varied with the fraction and size of the particles. Sang Won Lee and Sung Hyuk Park\cite{14} studied the static recrystallization mechanism in cold-rolled magnesium alloy based on quasi in situ EBSD observations and found that the shear bands and double twins act as recrystallization sites during annealing. Based on electron backscatter diffraction and convolutional multiple whole profile methods, Hyeon-Woo Son and Chang-Hee Cho et al.\cite{15} also studied the deformation banding and static recrystallization in high-strain-rate torsioned Al-Mg alloy and indicate that most deformation bands exhibit strain accumulation near their boundaries, which can accelerate SRX upon annealing.

The UHSSS we developed exhibits an ultimate tensile strength higher than 1.9 GPa, with a U-type impact toughness measured at room temperature higher than 40 J and good corrosion resistance. However, heavy alloy elements result in a significantly increasing carbides precipitation tendency during the thermal or thermomechanical treatment process, which further leads to complicated interaction between the carbide precipitation and SRX.\cite{16}. Hence, the effects of the deformation parameters, initial grain size and carbides on the SRX behavior of a new type of UHSSS were systematically investigated in this study.

| Table 1. The chemical composition (wt.%) of the studied UHSSS. |
|-----------------|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| C   | Cr  | Ni | Co | Mo | W + V | O | N | H | Fe |
| 0.14 | 13.0 | 2.0 | 14.0 | 5.0 | 2.0 | ≤0.005 | ≤0.005 | ≤0.005 | Bal. |

Figure 1. Schematic diagrams of the double-hit isothermal compression tests for studying the influence of (a) the deformation parameters and (b) the initial grain size on the SRX behavior.
2. Experimental

2.1. Materials and double-hit isothermal compression experiments

The nominal chemical composition of the studied UHSSS is given in table 1. A thermal compression test was performed using cylindrical samples ($\Phi 8$ mm $\times$ 12 mm) and a Gleeble-1500 thermal-mechanical simulator to study the SRX behavior. The double-hit hot compression process was elaborately designed and is illustrated in figure 1(a), and various combinations of deformation parameters were employed. The cylindrical samples were preheated to 1150 °C and homogenized for 5 min to obtain uniform and identical initial microstructures. Then, they were cooled to deformation temperatures of 1000 °C, 1050 °C, 1100 °C and 1150 °C for the first stage of the compression test, and both the heating and cooling rates were set as 10 °C s$^{-1}$. Specimens were initially deformed to true strains of 0.1, 0.15 and 0.2 at strain rates ranging from 0.1 to 5.0 s$^{-1}$. After that, the samples were held for various interstage times (1 s, 5 s, 20 s, 50 s and 100 s). Subsequently, the second stage compression was imposed with the same conditions as the first stage, and the specimens were quenched in water immediately after the second stage compression. Moreover, the deformation parameters were set to be constant to clarify the influence of the initial austenite grain size. The detailed hot deformation processes and the specific parameters are schematically demonstrated in figure 1(b). The cylindrical samples were first heated to 1150 °C and held for 10 s and 90 s to obtain different initial microstructures. Some of them were directly quenched in water to freeze the microstructure for initial austenite grain size measurement. The remaining samples were sent to the first stage of compression and deformed under the same deformation conditions ($\varepsilon = 0.15$, $T = 1100$ °C, and $\dot{\varepsilon} = 1.0$ s$^{-1}$). As the first stage compression finished, the samples were further held for various interstage times. After that, second-stage compression was implemented. Finally, the deformed specimens were treated by water quenching for subsequent microscopic observations.

2.2. Microstructure observation

The sections cut from the middle of the quenched samples were polished well and etched by a solution of 8 g KMnO$_4$, 10 ml H$_2$SO$_4$ and 90 ml H$_2$O for optical microscopy (OM, ZEISS-40MAT) observation. The prior austenite grain size was measured by the mean linear intercept method using image-pro plus software. The observation of fine precipitates was performed under a high-resolution transmission electron microscope (TEM) (Tecnai G2 F30 S-TWIN HRTEM). Mechanical grinding was first performed on the thin films used for

Figure 2. The influence of (a) the interpass time, (b) strain rate and (c) deformation temperature on the flow stress–strain curves.
TEM observation until their thickness was less than 40 μm. Then, these films were further reduced by twin-jet electropolishing in a solution of 8 ml HClO₄ and 92 ml C₂H₅OH at a temperature of approximately −20 °C.

3. Results

3.1. Flow curves of the double-hit isothermal compression tests

The influence of the holding time between two passes [see figure 2(a)] as well as the deformation conditions (i.e., T and \( \dot{\varepsilon} \)) [see figures 2(a), and, (b)] on the flow curves is shown in figure 2. The results in figure 2(a) show that the flow stress decreased with increasing interpass time from 1 s to 50 s. This suggests that the dislocations propagating during the first pass deformation were gradually eliminated by SRX softening during interpass annealing. However, when the holding time was further increased from 50 s to 100 s, the change in the flow stress did not have an effect, which implies that the process of SRX softening was almost finished. The influences of \( \dot{\varepsilon} \) and T on the flow stress are shown in figures 2(b), and, (c), respectively. Specifically, a decrease in \( \dot{\varepsilon} \) and an increase in T could both lead to a decrease in the flow stress. The flow stress of the second compression depends not only on the dislocation density accumulated in the first compression but also on the static restoration during the interpass time [10, 14]. Generally, higher dislocation density accumulates with a greater strain rate in the first hot compression, which consequently leads to a higher flow stress in the second pass. In addition, the static restoration was stimulated by raising the holding temperature between two passes, which led to a decrease in the flow stress of the second hot compression [4].

3.2. Static softening fraction

To determine the variation in the static softening fraction (X), the classical 2% offset method was used and is described in equation (1)

\[
X = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1} \times 100\%
\]
where $\sigma_s$ and $\sigma_m$ are the offset yield stress and peak stress obtained from the first pass flow curves, respectively, and $\sigma_t$ is the offset yield stress obtained from the second pass flow curves. The static softening fraction $X$ is assumed to be the same as the volume fraction of SRX ($X_{SRX}$) that all the softening is attributed to static recrystallization while softening by recovery is neglected [11].

In order to exclude the effect of MDRX on the softening fraction, the critical strain for DRX was first determined using the method Poliak and Jonas [17] have demonstrated, i.e. the critical stress for the onset of DRX, $\sigma_c$, is the lowest point at the curve of $-d\theta/d\sigma$ versus $\sigma$, and the results are shown in figure 3. The curves of $-d\theta/d\sigma$ versus $\sigma$ in figure 3 showed almost no lowest values, in other words, almost no DRX occurred, except which deformed at 1100 °C with strain rate, true strain and initial austenite grain size are $1 \text{s}^{-1}$, 0.1 and 11.3 μm [the black curve in figure 3(c)], with critical strain of DRX is 0.083, which is only 0.017 less than the true strain of the first pass deformation. Thus, almost all the softening is attributed to static recrystallization while softening by MDRX could be neglected.

The calculated results are shown in figure 4, and the influence of the initial grain size and deformation conditions on the static softening fraction were also studied. Obviously, the values of $X$ increased with increasing deformation temperature [see figure 4(a)], strain rate [see figure 4(b)] and true strain [see figure 4(c)] but decreased with increasing initial grain size [see figure 4(d)]. As one of the key driving forces for static recrystallization, dislocations are the main reason for the differences in the SRX softening rates obtained under different deformation conditions and initial grain sizes. The dislocation density accumulated during the first pass deformation increased with increasing strain rate and true strain but decreased with increasing initial grain size; furthermore, a higher dislocation density further generated a stronger driving force for SRX. In addition, more grain boundaries existed per unit volume in samples with fine initial grain sizes, supplying more nucleation sites for SRX, which could be another reason for the acceleration of the SRX softening rate.

However, the influence of the deformation temperature on the dislocation density evolution is present not only in the first pass deformation but also in the subsequent insulation process. Note that the static softening rate at 1000 °C was much lower than that at temperatures ranging from 1050 °C to 1150 °C. As shown in figure 4(d), when the interpass holding time was 1 s, the value of $X$ (~30%) at 1000 °C was almost the same as that at 1150 °C and increased only to 60% when the holding time was extended from 1 s to 100 s. However, when the sample was deformed at 1150 °C, the value of $X$ reached 100% as the holding time extended to 100 s. Interestingly, according
to the study of Liu et al.\cite{11} on 300 M steel, there are almost no differences between the static softening rates at low and high deformation temperatures. In other words, the static softening rate is very sensitive to the deformation temperature in the present study of UHSSS, which is quite different from that of 300M steel. Thus,

**Figure 5.** The SRX grains at different deformation temperatures (T), strain rates (\(\dot{\varepsilon}\)) and true strains (\(\varepsilon\)) with different initial grain sizes (\(d_0\)): (a) T = 1100 °C, \(\dot{\varepsilon}\) = 1 s\(^{-1}\), \(\varepsilon\) = 0.15, \(d_0 = 11.3 \mu m\); (b) T = 1100 °C, \(\dot{\varepsilon}\) = 1 s\(^{-1}\), \(\varepsilon\) = 0.15, \(d_0 = 23.6 \mu m\); (c) T = 1100 °C, \(\dot{\varepsilon}\) = 1 s\(^{-1}\), \(\varepsilon\) = 0.15, \(d_0 = 76.2 \mu m\); (d) T = 1000 °C, \(\dot{\varepsilon}\) = 1 s\(^{-1}\), \(\varepsilon\) = 0.2, \(d_0 = 76.2 \mu m\); (e) T = 1100 °C, \(\dot{\varepsilon}\) = 1 s\(^{-1}\), \(\varepsilon\) = 0.1, \(d_0 = 76.2 \mu m\); (f) T = 1150 °C, \(\dot{\varepsilon}\) = 1 s\(^{-1}\), \(\varepsilon\) = 0.15, \(d_0 = 76.2 \mu m\); (g) T = 1100 °C, \(\dot{\varepsilon}\) = 1 s\(^{-1}\), \(\varepsilon\) = 0.15, \(d_0 = 76.2 \mu m\); (h) T = 1100 °C, \(\dot{\varepsilon}\) = 0.1 s\(^{-1}\), \(\varepsilon\) = 0.15, \(d_0 = 76.2 \mu m\); (i) Influence of \(d_0\), \(\varepsilon\), and T, \(\dot{\varepsilon}\) on \(d_{SRX}\).
we can reasonably infer that there are factors affecting the SRX behavior apart from the deformation temperature. These factors are discussed in detail in the following sections together with microstructural observations.

### 3.3. Microstructural observation

The morphologies of the prior austenite grains after SRX under different deformation conditions are shown in figure 5, in which the specimens deformed under the same conditions were introduced to illuminate the influence of the initial grain size on the microstructural evolution of SRX. Figures 5(a)–(c) reveals that the features of the prior austenite grains after SRX varied with different initial grain sizes of 11.3 μm, 23.6 μm and 76.2 μm and that the average SRX grain sizes ($d_{SRX}$) were further measured to be 18.5 μm, 20.5 μm and 29.5 μm. Additionally, the effect of true strain over the range from 0.1 to 0.2 was investigated at a deformation temperature of 1100 °C and strain rate of 1 s$^{-1}$; these results are shown in figures 5(c)–(e). The $d_{SRX}$ of the samples deformed at true strains of 0.15, 0.2 and 0.1 were 29.5 μm, 22.1 μm and 34.7 μm, respectively. To further elucidate the influence of the deformation temperature, specimens were deformed at a strain rate of 1 s$^{-1}$ and true strain of 0.15. Figures 5(c), (f) and (g) show the microstructures of the corresponding specimens deformed at 1100 °C, 1150 °C and 1050 °C, and the values of $d_{SRX}$ were determined to be 29.5 μm, 41.3 μm and 13.5 μm, respectively. In addition, in the case of investigation of the strain rate, specimens were deformed at 1100 °C and a true strain of 0.15. As shown in figures 5(c) and, (h), the $d_{SRX}$ was determined to be 29.5 μm and 35.7 μm under strain rates of 1 s$^{-1}$ and 0.1 s$^{-1}$, respectively, indicating a decreasing tendency of the grain size with increasing strain rate.

Figures 6(a), (b) displays the equilibrium phase fractions of the UHSSS calculated by Thermo-Calc software (TCFe9 database). Note that $M_6C$ precipitated at temperatures below 1080 °C in the austenitic matrix. The TEM and energy dispersive spectroscopy (EDS) analysis results shown in figures 6(c) and, (d) clarify that these
precipitates are $M_6C$ carbides with compositions of 14.43Cr-9.63Co-13.00Mo-1.28W in weight percentage, which is consistent with the thermodynamic calculation results (see figure 6(b)). The pinning effect of precipitates can significantly hinder the migration of grain boundaries [18, 19], which further reduces the SRX softening rate. Therefore, in contrast to the fast softening rate at temperatures above 1050 °C, the steep decline in the softening rate at 1000 °C can be credibly verified.

Figure 7. Relationship between the processing parameters and static recrystallized grain size in the UHSSS: (a) $\ln d - \ln d_{\text{SRX}}$, (b) $\ln \varepsilon - \ln d_{\text{SRX}}$, (c) $\ln \varepsilon - \ln d_{\text{SRX}}$, and (d) $1/T - \ln d_{\text{SRX}}$.

Figure 8. Measured and predicted average grain sizes after SRX.
4. Modeling and discussion

4.1. SRX grain size model

Based on the microstructural observations shown in figure 5, $d_{SRX}$ primarily depends on the deformation parameters and initial grain size. Thus, the grain size model of SRX can be expressed as [20–22]:

$$d_{SRX} = A_0 d_0^r e^{s t} \exp \left( -\frac{Q}{RT} \right)$$  \hspace{1cm} (2)

where $A_0$, $r$, $s$, and $t$ are material constants and $Q$ and $R$ denote the SRX activation energy ($\text{kJ/mol}$) and gas constant ($\text{kJ/(mol·K)}$). Taking the natural logarithm of equation (2) gives:

$$\ln d_{SRX} = \ln A_0 + h \ln d_0 + k \ln \varepsilon + m \ln \varepsilon - \frac{Q}{RT}$$  \hspace{1cm} (3)

Figures 7(a)–(d) shows the relationships of $\ln d_0$, $\ln d_{SRX}$, $\ln \varepsilon$, $\ln d_{SRX}$, $\ln \varepsilon$, $\ln d_{SRX}$, and $1/T$–$\ln d_{SRX}$. The values of $A_0$, $r$, $s$, and $t$ can be readily determined to be $1.17 \times 10^8$, $0.25$, $-0.63$, and $-0.083$ from figure 7, respectively. The SRX activation energy ($Q$) can be calculated ($200.02 \text{ kJ/mol}$). Consequently, the static recrystallized grain size model of the UHSSS can be deduced as equation (4):

$$d_{SRX} = 1.17 \times 10^8 d_0^{0.25} e^{-0.63 \varepsilon - 0.083} \exp \left[ -\frac{200020}{RT} \right]$$  \hspace{1cm} (4)

The measured and predicted average grain sizes after SRX are shown in figure 8. Evidently, the predicted results are in good agreement with the measured results, showing that the model we established can reasonably predict the average grain size under different deformation conditions.
4.2. The kinetics model for static recrystallization

The kinetics of SRX can be characterized by the Avrami equation as follows [23–25]:

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

where \( n \) is the Avrami exponent, \( t \) is the interpass time, and \( t_{0.5} \) is the time corresponding to a recrystallization volume fraction of 50%, which is determined by the abovementioned deformation parameters, namely, \( \varepsilon, \dot{\varepsilon}, T \) and \( d_0 \), which can be calculated via equation (6) [26, 27]:

\[ t_{0.5} = A d_0^m \varepsilon^p \dot{\varepsilon}^q \exp\left(\frac{Q_s}{RT}\right) \]

where \( A, m, q \) and \( p \) are the Avrami exponents. To calculate the value of \( n \), equation (5) is changed to equation (7):

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

where \( n \) can be calculated by the slope of the plots of \( \ln(\ln(1/(1-X))) \)-ln\( t \). The average value of \( n \) is determined to be 0.437 by the linear regression method, as shown in figure 9. Then, the values of \( t_{0.5} \) under different conditions and initial grain size can be calculated, which are further used to determine the Avrami exponents (i.e., \( A, m, q \) and \( p \)) and the SRX activation energy, \( Q_s \), via the following equation:

\[ \ln t_{0.5} = \ln A + mlnd_0 + p\ln \varepsilon + q\ln \dot{\varepsilon} + \frac{Q_s}{RT} \]

The values of the Avrami exponents and the SRX activation energy can be determined by the slopes of the \( \ln t_{0.5} - 1/T \), \( \ln t_{0.5} - \ln \varepsilon \), \( \ln t_{0.5} - \ln \dot{\varepsilon} \), and \( \ln t_{0.5} - \ln d_0 \) plots shown in figure 10, while the values of \( Q_s, p, q \) and \( m \) are determined to be 209.62 kJ·mol\(^{-1}\), -1.534, -0.416 and 0.724, respectively. Additionally, \( A \) can be obtained by substituting the above material constants into equation (8). Finally, the SRX kinetics of the UHSSS can be obtained and expressed as equations (9) and (10)

Figure 10. The relationships between \( \ln(t_{0.5}) \) and (a) \( \ln(\varepsilon) \), (b) \( \ln(\dot{\varepsilon}) \), (c) \( 1/T \), and (d) \( \ln(d_0) \).
The measured and calculated values of the SRX fraction under different conditions and with different initial
grain sizes are plotted in figure 11. Apparently, the measured values of the SRX fraction above 1050
℃ exhibit an approximate linear relationship with the calculated values, which implies that the established SRX model can
accurately predict the SRX grain size under different deformation conditions. In particular, the simulation of the
SRX during deformation at a strain rate of 0.1 s$^{-1}$ and true strain range from 0.1 to 0.2 shows that SRX is

Figure 11. The experimental (represented as curves) and the calculated (represented as scatter) X of samples deformed under different
conditions, namely, (a) ε, (b) $\dot{\varepsilon}$, (c) T with different $d_0$.

Figure 12. The optical micrograph of SRX grains after deformation at different conditions and holding for 100 s; (a) T = 1000 °C,
$\dot{\varepsilon} = 0.1$ s$^{-1}$, $\varepsilon = 0.15$, $d_0 = 76.2$ μm, (b) T = 1150 °C, $\dot{\varepsilon} = 1$ s$^{-1}$, $\varepsilon = 0.15$, $d_0 = 76.2$ μm.

\[
X_s = 1 - \exp \left( -0.693 \left( \frac{t}{t_{0.5}} \right)^{0.437} \right)
\]  

\[
t_{0.5} = 9.24 \times 10^{-13} d_0^{0.724} e^{-1.534 e^{-0.416 \exp \left( \frac{209617}{RT} \right)}}
\]  

The measured and calculated values of the SRX fraction under different conditions and with different initial
grain sizes are plotted in figure 11. Apparently, the measured values of the SRX fraction above 1050 °C exhibit an
approximate linear relationship with the calculated values, which implies that the established SRX model can
accurately predict the SRX grain size under different deformation conditions. In particular, the simulation of the
SRX during deformation at a strain rate of 0.1 s$^{-1}$ and true strain range from 0.1 to 0.2 shows that SRX is
significantly hindered when the deformation temperature is lower than 1050 °C [see figures 11(a) and, (c)] due to the stronger suppression of M6C carbides during deformation, which is consistent with the results in figure 4(d). The results of microscopic observation were shown in figures 12(a), and (b), SRX fractions of specimens deformed at 1000 °C and 1150 °C were 50% and 100% respectively, which proved that the experimental SRX fractions was lower than the calculated SRX fractions when deformed lower than 1050 °C.

Hereafter, based on the above experimental results and analysis, the correlation among the deformation parameters, initial austenite grain size and SRX grain size was verified, and numerical and kinetic models were proposed.

5. Conclusions

The static recrystallization (SRX) behavior of a novel ultrahigh-strength stainless steel (UHSSS) was studied by considering the influence of both the deformation conditions and initial microstructures. The main results are summarized as follows:

1. The SRX kinetics of the studied UHSSS could be significantly affected by the deformation parameters (i.e., 
   \( T, \varepsilon, \dot{\varepsilon} \)) as well as the microstructure characteristics of the specimens, namely, the precipitated phase and initial austenite grain size. The SRX kinetics were accelerated by increases in \( T, \varepsilon \) and \( \dot{\varepsilon} \) while decreasing with an increase in initial austenite grain size. In addition, the precipitated phase detected below 1050 °C was determined to be M6C carbides, which could inhibit the process of SRX. The quantitative model for the SRX kinetics we developed could predict the softening behavior at deformation temperatures ranging from 1050 °C to 1150 °C well. Moreover, the unusual retardation of SRX when the deformation temperature was lower than 1050 °C in some cases was successfully simulated:

\[
X = 1 - \exp \left( -0.693 \left( \frac{t}{t_{0.5}} \right)^{0.437} \right)
\]

\[
t_{0.5} = 9.24 \times 10^{-13} d_0^{0.724} \varepsilon^{-1.534} \dot{\varepsilon}^{-0.416} \exp \left( \frac{209617}{RT} \right)
\]

2. The microstructural observations showed that the grain size of the initial austenite and strain rate had a strong influence on the statically recrystallized grain size. When the static softening fraction was close to or above 95%, the equation of statically recrystallized grain size could be described as:

\[
d_{SRX} = 1.17 \times 10^8 d_0^{0.25} \varepsilon^{-0.65} \dot{\varepsilon}^{-0.083} \exp \left( - \frac{200020}{RT} \right)
\]

ORCID iDs

Xiao-hui Wang https://orcid.org/0000-0002-1560-5710

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