Materials Research Express

OPEN ACCESS

PAPER

Kinetic model of dynamic recrystallization of DP1000 steel for auto body structures

Hui Li*1, Feng Rui1, Cui Xiao-li1, Pan Yao-kun2, Fu Xue-jie3 and Ding Xuan∗2

1 School of Materials Science and Engineering, Shandong University of Technology, Zibo 255000, People’s Republic of China
2 College of Engineering, Yantai Nanshan University, Yantai 265700, Shandong, People’s Republic of China

* Author to whom any correspondence should be addressed.

E-mail: lhlwj8888@163.com (Li Hui)

Keywords: DP1000 steel, kinetic model, dynamic recrystallization, auto lightweight

Abstract

Hot compression tests were performed in DP1000 steel under a temperature range of 950 ~ 1150 °C with
corresponding strain rate of 0.05 ~ 10 s−1 to investigate the kinetic model of dynamic recrystallization
(DRX) on a Gleeble 3800 thermal simulation test machine. The characteristic parameters such as critical
stress/strain (σc/εc), peak stress/strain (σp/εp), maximum softening stress/strain (σm/εm) and steady-
state stress/strain (σsw/εsw) were acquired according to the stress-strain data. The beginning of DRX
was found from the inflection point of the cubic spline θ−σ curve. The Zahiri model was used to calculate
the DRX percentage. The revised MZ DRX model based on multiple characteristic parameters was developed,
and the prediction value had good agreement with the experimental results.

1. Introduction

The increasing depletion of energy and the continuous deterioration of the environment put forward higher
requirements for automobile energy saving and emission reduction. Recently, the strategy of reducing driving
resistances, especially vehicle weight, has been reported as a potential route for the reduction in energy
consumption [1, 2]. The application of high strength steels is one of the important means of automobile
lightweight. Advanced high strength steels mainly include dual phase (DP) steel, transformation induced
plasticity (TRIP) steel, twinning induced plasticity (TWIP) steel and quenching and partitioning (Q&P) steel
[3, 4]. DP steel is one of the most widely used steels. The two-phase composite structure of ferrite and
martensite/bainite in DP steel gives it the advantages of continuous yield, high strain hardening rate and good
combination of strength and ductility.

At present, the research on hot rolled DP steel mainly focuses on the influence of alloy elements and cooling
process on microstructure evolution and mechanical properties, while the research on dynamic recrystallization
(DRX) during hot deformation process is rare. The mathematical model of DRX is established by
phenomenological Johnson–Mehl-Avrami equation. Many researchers have studied the model. Huang [5]
studied the DRX behavior of 300M steel and found that the nucleation mechanism was determined to mainly
involve bulging of the initial grain boundaries, and established the hot processing map which involving the DRX
region based on a dynamic material model. Chen [6] investigated the hot deformation and DRX behaviour of
40Cr steel, and found that low strain rate and high temperature were beneficial for the occurrence of DRX, and
established the relationship between DRX grain size and Zener–Holloman parameters. Wang [7] thought that
DRX nucleation performed in grain boundary bulging mechanism and subgrain growth mechanism. Saadatkia
[8] concluded that the flow stress of plain carbon steel in hot deformation was mainly controlled by dislocation
climb during their intragranular motion. Ji [9] proved that the materials constants of 42CrMo steel had similar
relationship with Z parameter and established the dynamic recrystallization volume fraction model. Xu [10]
determined the activation energy of DRX and Z parameter by regression analysis of stress–strain data of X70 steel
and revised the Avrami equation. Chen [11] developed the DRX region diagram to show the effect of
deformation parameters on the DRX evolution of a modified 21Cr-11Ni-N-RE lean austenitic steel. Razali [12]
presented a new approach of predicting the DRX using directly a flow stress model of medium Mn steel which has better accuracy than JMAK equation. Zhao\cite{13} established the DRX kinetic model and recrystallization grain size model of 300M steel, and proved that strain-induced boundary migration mechanism and curvature-driven grain boundary migration mechanism were the main mechanism. Han\cite{14} identified the critical conditions for initiating DRX by using Z-H parameter and calculated the activation energy. It can be seen from above that the strain, strain rate and temperature has obvious effect on DRX behavior of different steels.

Different scholars put forward different modified models for different steel grades and the main difference is lied in the way of determining the critical stress and the grain size after recrystallization. The work on dynamic model of DRX of DP1000 steel remains incomplete.

Therefore, this work studies the hot deformation behavior of DP1000 steel through thermal simulation test, different DRX models are compared and optimized, and the microstructure evolution is analyzed, so as to provide a theoretical basis for formulating and optimizing hot rolling process.

2. Materials and experimental methods

2.1. Acquisition of flow stress
The 0.16C-0.62Si-2.02Mn-0.03Nb-0.45Cr (wt\%) DP1000 steel was used in this experiment, and the ingot was processed into cylindrical specimens with a diameter of 10 mm and a height of 15 mm. Gleeble3800 thermal simulation test machine was used to carry out the single pass hot compression experiment at constant temperature and constant strain rate. Before the experiment, both ends of the specimen were polished and coated with high temperature lubricant to reduce the effect of friction.

The sample was heated to 1200 °C at a rate of 5 °C/s and kept at 1200 °C for 5 min, then cooled to deformation temperature at 5 °C/s and homogenized for 30 s, finally the single pass hot compression was carried out at different strain rates. In the process 1, the deformation amount was 50% and the deformation temperature was 950 °C, 1000 °C, 1050 °C, 1100 °C and 1150 °C respectively, with corresponding strain rate of 0.05 s\(^{-1}\), 0.1 s\(^{-1}\), 1 s\(^{-1}\), 5 s\(^{-1}\) and 10 s\(^{-1}\) for each deformation temperature. In the process 2, the deformation amount was 15%, 28% and 55% respectively with a deformation temperature of 1050 °C and a strain rate of 0.05 s\(^{-1}\). For process 2, the specimens were quenched immediately after compression to retain the hot deformed austenite structure. The hot compression specimen after water quenching was cut along the center, and the grain boundary was corroded by saturated picric acid solution (corrosion temperature 65 °C). The microstructure at 1/4 distance from the compression end was observed using Axio Imager M2m optical microscope.

2.2. Determination of characteristic parameters
The critical stress/strain (\(\sigma_c/\varepsilon_c\)), peak stress/strain (\(\sigma_p/\varepsilon_p\)), maximum softening stress/strain (\(\sigma_m/\varepsilon_m\)) and steady-state stress/strain (\(\sigma_{ss}/\varepsilon_{ss}\)) are the characteristic parameters during thermal deformation of materials. These parameters reflect the microstructure evolution to a certain extent, and are also indispensable in building the dynamic model.

The peak value and steady-state stress can be obtained directly through the tested stress-strain curves, while other characteristic parameters must be obtained through the work hardening rate curve (\(\theta-\sigma\)), as shown in figure 1, in which the work hardening rate is calculated according to \(d\sigma/d\varepsilon\). It can be seen that after a short
proportional loading stage (generally $\sigma_{0.02}$), the deformation enters stage I during which the dynamic recovery (DRV) mechanism starts and the work hardening rate $\theta$ begins to decrease linearly. With the further deformation, the dislocation density increases gradually, and the sub grain begins to form inner the original austenite grains due to the slip and climb of dislocations. The deformation enters stage II during which the effect of DRV weakens and the decrease rate of $\theta$ slows down [15]. With the further increase of dislocation density, the driving force of recrystallization increases gradually. When the critical value of recrystallization is reached, the DRX begins. The decrease rate of $\theta$ becomes faster, and the inflection point of $\theta$- $\sigma$ appears. According to the research of Poliak and Jonas [16], this inflection point was the appearance point of the additional thermodynamic degree of freedom of the material during hot deformation, and it was the sign of the beginning of recrystallization. After this point, the deformation enters stage III. During this stage, $\theta$ decreases rapidly to zero. At the same time, the flow stress reaches the peak $\sigma_p$, and then continues to decrease to the minimum. At this time, the dynamic softening effect is the strongest, and the corresponding flow stress is the maximum softening stress, $\sigma_m$. Finally, $\theta$ increases again and finally returns to zero, and the flow stress reaches the steady state, $\sigma_s$. For continuous DRX and single peak discontinuous DRX, the work hardening, DRV and DRX softening reach dynamic equilibrium after the material enters the steady-state deformation, and the flow stress will not change with the increase of deformation. The upwarping of the curve may be due to the increase of friction at both ends of the specimen with the increase of deformation. It can be seen that $\sigma_p$, $\varepsilon_p$, $\sigma_m$, $\varepsilon_m$, $\sigma_s$ and $\varepsilon_s$ can be read directly from the $\theta$- $\sigma$ curve.

2.2.1. Determination of critical stress and strain
The stress/strain at the beginning of recrystallization is called critical stress/strain, which is the inflection point of $\theta$- $\sigma$ curve. Because of the discontinuity of the measured data, it is difficult to determine the inflection point by direct derivation. Therefore, Najafizadeh and Jonas [17] proposed a method to determine the critical stress by fitting the $\theta$- $\sigma$ curve with cubic spline curve and using its inflection point, as shown in figure 2. This method was widely accepted by researchers and was used to calculate the critical characteristic parameters of material thermal deformation [18–20]. The solution process is as followed.

$$\theta = A \sigma^3 + B \sigma^2 + C \sigma + D$$  
(1)

$$\sigma_c = -\frac{3A}{B}$$  
(2)

2.2.2. Determination of dynamic recovery stress and saturation stress
In the process of plastic deformation, work hardening and DRV softening take place simultaneously, and finally reach the equilibrium state with the increase of deformation. The DRV stress is an important parameter to calculate the DRX percentage. However, when the material is deformed above the recrystallization temperature, there are two softening modes of DRV and DRX. The stress-strain curve is the result of work hardening, DRV softening and DRX softening. Therefore, the DRV stress of the material can’t be obtained directly from the curve, so it needs to be obtained by calculation. Based on the dislocation density principle, Estrin and Mecking [21] considered that the dislocation growth rate was a certain value in the plastic deformation stage, and its DRV stress can be described by formula (3), and the peak value was the saturation stress. Whereas Zahiri [22] believed
that the work hardening rate was decreased linearly to zero after the thermal deformation reached the critical
stress, which was the saturation stress, as shown in figure 3. Through this linear relationship, the DRV stress
model (formula (6)) can be obtained.

 Estrin-Mecking (EM) model:

\[
\sigma_e = [\sigma_0^2 + (\sigma_s^2 - \sigma_0^2) \exp(-2B\varepsilon)]^{1/2}
\]

(3)

\[
\theta \sigma = A - B\sigma^2 \quad (\sigma_0 < \sigma < \sigma_s)
\]

(4)

\[
\sigma_s = \sqrt{\frac{A}{B}}
\]

(5)

in which \(\theta\) is the work hardening rate; \(\sigma_s\) is the saturation stress (MPa); A and B are material constants.

 Zahir (Z) model:

\[
\sigma_e = -\frac{\theta_t \exp[k_i(\varepsilon_c - \varepsilon)] - b}{k_i}
\]

(6)

\[
k_i = \frac{\theta_t}{\sigma_e - \sigma_c}
\]

(7)

\[
b = \frac{\theta_t \cdot \sigma_c}{\sigma_e - \sigma_c}
\]

(8)

in which \(\theta_t\) is the work hardening rate under critical stress; \(\sigma_c\) is the critical stress (MPa); \(b\) and \(k_i\) are constants.

In this work, the DRV stress and saturation stress of the experimental steel were obtained based on the EM
model and Z model respectively. The starting point of EM model was \(\sigma_0\), and the starting point of Z model was
\(\sigma_c\). The results are shown in figure 3.

The DRV stress obtained by the two models both gradually increases with the strain, and finally tends to a
certain value, which is the saturation stress. The saturation stress \(\sigma_s\) obtained by the two models is basically the
same, but the DRV stress obtained by Z model is closer to the saturation stress than that obtained by the EM
model. The fitting results of the two models under low strain are different. The DRV stress calculated by Z model
is above the stress-strain curve, and the difference between the DRV stress and the flow stress increases gradually
with the increase of strain, as shown by the green dotted line in figure 3. However, there is a small negative
deviation between the DRV stress and the stress-strain curve calculated by EM model. With the increase of the
strain, the deviation first increases and then decreases, and finally intersects with the stress-strain curve at a
certain strain. With further increase of the strain, the deviation gradually deviates with the stress-strain curve,
and the difference between the DRV stress and the flow stress gradually increases, as shown in the red dotted line.
The fitting results are similar to those of Estrin-Mecking [21]. After the critical strain, the softening effect of DRX
gradually increases, and the flow stress should be less than the DRV stress. Therefore, Z model is more in line
with the actual situation, which is adopted in this work to calculate the DRV stress and saturation stress of
materials.

Figure 3. DRV stress and saturation stress.
3. Experimental results and discussion

3.1. True stress and true strain curve

The stress-strain curves under different deformation conditions are shown in Figure 4. It can be seen that the flow stress increases rapidly and finally tends to be stable slowly at low temperature and high strain rate, which is a DRV curve. However, at high temperature and low strain rate, the flow stress shows DRX characteristic which increases rapidly to the peak value, then decreases and finally reaches a stable value. DRX is the main reason for the difference of flow stress characteristics. In the initial stage of deformation, the dislocation density increases rapidly. After reaching a certain critical value, the DRV mechanism starts. The slip, climb and cross slip of dislocations make some dislocations cancel each other, and macroscopically the work hardening rate slows down. However, the DRV softening is not enough to offset all the work hardening. Therefore, the deformation resistance and dislocation density continue to increase. When the critical value of DRX is reached, the recrystallization softening mechanism starts. With the further increase of deformation and dislocation density, the driving force of recrystallization gradually increases. The dual softening effect of recrystallization and DRV

Figure 4. True stress-true strain curves under different deformation conditions. (a) 0.05 s⁻¹; (b) 0.1 s⁻¹; (c) 1 s⁻¹; (d) 5 s⁻¹; (e) 10 s⁻¹.
gradually exceeds the work hardening effect, and the flow stress begins to decrease and finally reaches the steady state. Consequently, DRX, DRV and work hardening reach dynamic equilibrium.

The flow stress is highly sensitive to the deformation temperature and strain rate. With the increase of deformation temperature and the decrease of strain rate, the flow stress decreases obviously. The main reason is that high temperature enhances the atomic kinetic energy, improves the grain boundary mobility and promotes the nucleation and growth of austenite. While the decrease of strain rate prolongs the recrystallization time under unit strain, increases the recrystallization percentage and enhances the softening effect [23].

### 3.2. Volume fraction of dynamic recrystallization

In order to obtain the parameters of the kinetic model, the recrystallization percentage under different deformation conditions must be obtained. The workload of traditional method relying on metallographic

---

**Table 1. Calculation model of fraction of recrystallization.**

| Researchers                          | Mathematical model         |
|--------------------------------------|----------------------------|
| Jonas J [24]                         | \( X_{\text{DRX}} = \frac{\sigma - \sigma_0}{\sigma_0 - \sigma} \) |
| H Mirzadeh, A Najafizadeh [25]       | \( X_{\text{DRX}} = \frac{\sigma - \sigma_0}{\sigma_0 - \sigma} \) |
| Z Yang, Y C Guo [26]                 | \( X_{\text{DRX}} = \frac{\sigma_1 - \sigma}{\sigma_1 - \sigma_0} \) |
| Saden H Zahiri [22]                  | \( X_{\text{DRX}} = \frac{\sigma_1 - \sigma}{\sigma_1 - \sigma_0} \) |

---

**Figure 5.** Calculation results of recrystallization percentage of different models (1100 °C, 0.05 s⁻¹).

**Figure 6.** Recrystallization percentage under different deformation conditions (a)0.05 s⁻¹, (b)1150 °C.
measurement is heavy, and the accuracy of numerical value varies from person to person. Therefore, many researchers put forward the calculation method of recrystallization percentage by using stress-strain curve [24–26], as shown in table 1. The Jonas model and Najafizadeh model have no clear physical meaning, while Guo Model and Zahiri model are derived from the dislocation density principle and have clear physical meaning.

The calculation results of the four models are shown in figure 5. The calculation accuracy and the fitting effect of the Jonas model is better than the Najafizadeh model. Therefore, Jonas model is widely used as a classical model. Guo model takes the peak point as the starting point of recrystallization percentage calculation, and the data between the critical point and the peak point is lost which affects the calculation accuracy. Moreover, according to the previous literature [27], the recrystallization percentage at the peak point should be 15–20%, and the calculated value of Guo model is 74% which is obviously high. The calculation result of Zahiri model is basically consistent with the classical Jonas model, and have clear physical meaning. Therefore, Zahiri model is used in this work, the calculation results are shown in figure 6.

Since there is no obvious recrystallization softening at low deformation temperature and high strain rate (figures 4(d) (e)), this work only lists the recrystallization percentage at high temperature and low strain rate. It shows that the percentage of recrystallization gradually increases with the increase of strain, and finally approaches 100%. It also indicates that the recrystallization rate is related to the deformation conditions. Under the same strain, the recrystallization percentage increases with the increase of deformation temperature and decrease of strain rate.

3.3. Kinetic model of dynamic recrystallization
Avrami equation is generally used to describe the DRX kinetics. When the strain rate is constant, Avrami equation [24] can be expressed as:

![Figure 7. Average recrystallization percentage at maximum softening strain.](image)

| Model | Proposer | $\varepsilon^*$ | Expression |
|-------|----------|-----------------|------------|
| ST model | Sellars and Target [28] | $\varepsilon^* = \varepsilon_p$ | $X_{\text{DRX}} = 1 - \exp \left( -k \frac{\varepsilon - \varepsilon_c}{\varepsilon_p} \right)$ |
| KY model | Kim-Yoo [29] | $\varepsilon^* = \varepsilon_m$ | $X_{\text{DRX}} = 1 - \exp \left( -k \frac{\varepsilon - \varepsilon_c}{\varepsilon_m} \right)$ |
| JC model | JW Cahn [30] | $\varepsilon^* = \varepsilon_c$ | $X_{\text{DRX}} = 1 - \exp \left( -k \frac{\varepsilon - \varepsilon_c}{\varepsilon_m} \right)$ |
| Gao model | Gao [31] | $\varepsilon^* = \varepsilon_m - \varepsilon_c$ | $X_{\text{DRX}} = 1 - \exp \left( -k \frac{\varepsilon - \varepsilon_c}{\varepsilon_m - \varepsilon_c} \right)$ |
\[ X_{\text{DRX}} = 1 - \exp \left[ -k \left( \frac{\varepsilon - \varepsilon^*}{\varepsilon^*} \right)^n \right] \]

in which \( X_{\text{DRX}} \) is the fraction of recrystallization; \( \varepsilon^* \) is a characteristic strain; \( k \) and \( n \) are material constant.

Many researchers have proposed different kinetic models of DRX based on Avrami equation, and they mainly focus on the value method of \( \varepsilon^* \) [28–30]. This work lists four different models, as shown in table 2. It is worth noting that Stewart and Elwazri [27] found that the recrystallization percentage corresponding to the maximum softening strain is 50%, which was verified by experiments. The recrystallization percentage under the maximum softening strain under different deformation conditions is calculated, as shown in figure 7, and the average value is 51.09%. Therefore, it can be assumed that the recrystallization percentage under the maximum softening strain of the experimental steel is 50%. Based on this assumption, when \( \varepsilon = \varepsilon_{\text{m}}, X_{\text{DRX}} = 1 - \exp(-k) = 0.5 \), that is, the value of \( k \) should be 0.693, and the Z model will be modified as follows:

Figure 8. The solution of material constant of dynamic model. (a) MZ, (b) Gao, (c) KY, (d) JC, (e) ST.
In this work, the above formula (10) is called as modified Z model (hereinafter referred to as MZ model). These five models are used and are verified by the experimental data, so as to find the most suitable kinetic model for the experimental steel.

Taking logarithm on both sides of formula (10), it can be reduced to:

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

By fitting the linear relationship between $\ln \left[ - \ln \left(1 - X_{\text{DRX}} \right) \right]$ and $\ln \left( \frac{\varepsilon - \varepsilon_c}{\varepsilon_m - \varepsilon_c} \right)$, the material constants $n$ and $k$ under different deformation conditions can be obtained. Using the experimental recrystallization
percentage $X_{\text{DRX}}$ under the strain rate of $0.05 \sim 0.1 \text{ s}^{-1}$ and the deformation temperature of $950 \sim 1150^\circ\text{C}$, the material constants of the above five models are obtained respectively, as shown in figure 8.

The kinetic equations are obtained as follows:

- **MZ model**
  \[
  X_{\text{DRX}} = 1 - \exp\left[-0.693\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_m - \varepsilon_c}\right)^{1.97415}\right] \tag{12}
  \]

- **Gao model**
  \[
  X_{\text{DRX}} = 1 - \exp\left[-0.53027\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_m - \varepsilon_c}\right)^{2.02653}\right] \tag{13}
  \]

- **KY model**
  \[
  X_{\text{DRX}} = 1 - \exp\left[-1.10984\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_m}\right)^{1.86567}\right] \tag{14}
  \]

- **JC model**
  \[
  X_{\text{DRX}} = 1 - \exp\left[-0.12631\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_c}\right)^{1.82832}\right] \tag{15}
  \]

- **ST model**
  \[
  X_{\text{DRX}} = 1 - \exp\left[-0.693\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_p}\right)^{1.85095}\right] \tag{16}
  \]

In order to confirm the accuracy of these models, the percentage of DRX at the strain rate of $1 \text{ s}^{-1}$ and deformation temperature of $1050^\circ\text{C} \sim 1150^\circ\text{C}$ is calculated respectively, and is compared with the experimental values obtained above, as shown in figure 9. Since the experimental values of recrystallization percentage under this deformation condition are not involved in the calculation of model parameters, the results are objective and reliable. Due to the small recrystallization percentage at the initial stage, the small jump of the model calculation results will also lead to large relative error. Moreover, although the critical strain is the starting point of recrystallization, the obvious softening of flow stress starts from the peak strain [32]. Therefore, this work only considers the accuracy of the calculated value after the peak strain.

The accuracy of the model is usually verified by the statistical parameters such as maximum relative error $\delta$, average relative error AARE and correlation coefficient $R$. The calculation methods are shown in formula (17)–(19).
In the formula, \( E_i \) and \( P_i \) are the experimental and calculated values of recrystallization percentage, respectively; \( \bar{E} \) and \( \bar{P} \) are the arithmetic mean values of \( E_i \) and \( P_i \), respectively; \( N \) is the number of points.

The maximum relative errors of MZ model, Gao model, JC model, KY model and ST model are 15.6%, 27.2%, 29.1%, 26.3% and 37.5% respectively. It can be seen that the simulation results of the models considering both critical strain and maximum softening strain (Gao and MZ) are better than those by the models only considering one strain (JC, KY and ST). The main reason is that the DRX percentage is closely related to the characteristic parameters of strain and thermal deformation. Therefore, the accuracy of the model based on multiple characteristic parameters is better than that based on single characteristic parameter. For MZ model and Gao model, the former is better than the latter in predicting the recrystallization percentage after the peak strain. The reason is that the time constant of the MZ model is a fixed value, which makes the intercept of the fitting line constant. To some extent, the deviation caused by the deviation of the experimental value of recrystallization percentage under low strain is avoided.

### 3.4. Microstructure evolution

The recrystallization percentages of the experimental steel under 15%, 28% and 55% deformation at 1050 °C and strain rate of 0.05 s\(^{-1}\) are calculated by formula (12). The results are 7.6%, 50.2% and 94.5% respectively, as shown in figure 10. Their microstructures are shown in figure 11. The critical strain, the maximum softening strain and the steady-state strain of the experimental steel are 0.082, 0.286 and 0.519 respectively. It suggests that there is little difference between the calculated recrystallization percentages and the experimental values.

There is no recrystallized austenite grain at 15% strain, but the straight grain boundary between the original austenite grains fluctuates and forms a ‘zigzag’ grain boundary. The deformation mismatch between the adjacent original austenite grains leads to the local strain and the bulge of the grain boundary. This ‘zigzag’ grain boundary is the sign of the beginning of DRX. With the continuous deformation, the dislocation density at the bulge of the grain boundary continues to increase, and then the sub grain boundary or twin boundary is formed. With the migration of the grain boundary, final nucleation is formed [33]. At 28% strain, a large number of fine recrystallized grains appear around the original austenite grains, and this internal structure is called ‘necklace’ structure. The main reason for its formation is that in the process of continuous deformation, new recrystallized grains always nucleate repeatedly and grow continuously at the grain boundaries of the nucleated and growing grains until they completely replace the original austenite grains [34]. At this stage, the recrystallization percentage is 50.2%, and the recrystallization state is partial recrystallization. At 55% strain, the recrystallization percentage is 94.5%, and the recrystallization is nearly completed. The evolution process of recrystallization microstructure of the experimental steel is from ‘zigzag’ grain boundary (\( \varepsilon_c \)) to ‘necklace’ structure (\( \varepsilon_m \)) and finally equiaxed crystal (\( \varepsilon_{ea} \)).
4. Conclusion

The flow stress of the experimental DP1000 steel is very sensitive to the deformation temperature and strain rate. There are two main characteristics of stress-strain curves under different deformation conditions: DRV curves at low temperature and high strain rate, and DRX curves at high temperature and low strain rate.

The revised MZ DRX model is established which can better reflect the DRX kinetic of the experimental DP1000 steel. The maximum relative error is 15.6%, AARE is 8.28% and correlation coefficient R is 0.988. With the increase of strain, the DRX percentage increases gradually and finally approaches 100%. The microstructure evolution process is from ‘zigzag’ grain boundary to ‘necklace’ structure and finally equiaxed crystal.

Acknowledgments

The work was financially supported by A Project of Shandong Province Higher Educational Science and Technology Program, China (Grant No. 2019KJA019), Shandong Provincial Natural Science Foundation of China (Grant number. ZR2018MEM007).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of Interest

The authors declare no conflicts of interest.

ORCID iDs

Hui Li https://orcid.org/0000-0002-8333-4916

References

[1] Chang Y et al 2018 Investigation of forming process of the third-generation automotive medium-Mn steel part with large-fractioned metastable austenite for high formability Mater. Sci. Eng. A 721 179–88
[2] Venezuela J et al 2020 Hydrogen embrittlement of an automotive 1700 MPa martensitic advanced high-strength steel Corros. Sci. 171 1–11
[3] Ding H.L. et al 2020 Excellent combination of plasticity and ultra-high strength in a low-alloy automotive steel treated by conventional continuous annealing Mater. Sci. Eng. A 791 1–9
[4] Li H et al 2018 Hot deformation behaviour and processing map of a typical Fe-Mn-Si-Cr steel for automotive body structures Ironmaking & Steelmaking 45 937–43
[5] Li C.M et al 2020 Influence of hot deformation on dynamic recrystallization behavior of 300M steel: rules and modeling Mater. Sci. Eng., A 797 1399–25
[6] Chen L et al 2019 Modelling of constitutive relationship, dynamic recrystallization and grain size of 40Cr steel during hot deformation process Results in Physics 12 784–92
[7] Wang S.L et al 2016 Study on the dynamic recrystallization model and mechanism of nuclear grade 316LN austenitic stainless steel Mater. Charact. 118 92–101
[8] Saadatkia S, Mirzadeh H and Cabrera J M 2015 Hot deformation behavior, dynamic recrystallization, and physically-based constitutive modeling of plain carbon steels Mater. Sci. Eng., A 636 196–202
[9] Ji H.C et al 2020 Optimization the working parameters of as-forged 42CrMo steel by constitutive equation-dynamic recrystallization equation and processing maps Journal of Materials Research and Technology 9 7210–24
[10] Xu Y W et al 2012 Dynamic recrystallization kinetics model of X70 pipeline steel Materials & Design 39 168–74
[11] Chen L.et al 2016 Modeling of dynamic recrystallization behavior of 21Cr-11Ni-N-RE lean austenitic heat-resistant steel during hot deformation Mater. Sci. Eng., A 663 141–50
[12] Razafi M K and Joun M S 2021 A new approach of predicting dynamic recrystallization using directly a flow stress model and its application to medium Mn steel Journal of Materials Research and Technology 11 1881–94
[13] Zhao M G et al 2020 In-situ observations and modeling of metadynamic recrystallization in 300M steel Mater. Charact. 159 109997
[14] Han Y et al 2018 Effects of temperature and strain rate on the dynamic recrystallization of a medium-high-carbon high-silicon bainitic steel during hot deformation Vacuum 148 78–87
[15] Ryan N D and Mcqueen H J 1990 Flow stress, dynamic restoration, strain hardening and ductility in hot working of 316 steel[J] Journal of Materials Processing Tech 21 177–99
[16] Poliak E I and Jonas J J 1996 A one-parameter approach to determining the critical conditions for the initiation of dynamic recrystallization[J] Acta Materialia 44 127–36
[17] Najafizadeh A and Jonas J J 2006 Predicting the critical stress for initiation of dynamic recrystallization ISIJ Int. 46 1679–84
[18] Zhang Y et al 2016 Hot deformation and dynamic recrystallization behavior of the Cu-Cr-Zr-Y alloy Journal of Materials Engineering & Performance 25 1150–6

[19] Li Y P et al 2016 Hot deformation and dynamic recrystallization behavior of austenite-based low-density Fe–Mn–Al–C steel Acta Metallurgica Sinica 29 1–9

[20] Wan Z et al 2017 Experimental study and numerical simulation of dynamic recrystallization behavior of TiAl-based alloy Materials & Design 122 11–20

[21] Haghdfadi N, Martin D and Hodgson P 2016 Physically-based constitutive modelling of hot deformation behavior in a LDX 2101 duplex stainless steel Mater. Des. 106 420–7

[22] Zahiri S H, Davies C H J and Hodgson P D 2005 A mechanical approach to quantify dynamic recrystallization in polycrystalline metals Scripta Materialia 52 299–304

[23] Zhang P et al 2016 Constitutive model based on dynamic recrystallization behavior during thermal deformation of a Nickel-based superalloy Metals 6 161

[24] Jonas J et al 2009 The avrami kinetics of dynamic recrystallization Acta Mater. 57 2748–56

[25] Ferdowis M R G et al 2014 Modeling the high temperature flow behavior and dynamic recrystallization kinetics of a medium carbon microalloyed steel Journal of Materials Engineering & Performance 23 1077–87

[26] Yang Z et al 2008 Plastic deformation and dynamic recrystallization behaviors of Mg–5Gd–4Y–0.5Zn–0.5Zr alloy Materials Science & Engineering A 485 187–91

[27] Stewart G R et al 2013 Modelling of dynamic recrystallisation kinetics in austenitic stainless and hypereutectoid steels Materials Science & Technology 22 519–24

[28] Sellars C M and Tegart W J M 1972 Hot workability Int. Mater. Rev. 17 1–24

[29] Kim S I and Yoo Y C 2001 Dynamic recrystallization behavior of AISI 304 stainless steel Materials Science & Engineering A 311 108–13

[30] Cahn J W 1956 The kinetics of grain boundary nucleated reactions Acta Metall. 4 449–59

[31] Gao Z Y et al 2015 Hot deformation behavior of a novel Ni–Cr–Mo–B ultra-heavy plate steel by hot compression test Journal of Iron and Steel Research, International 22 818–26

[32] Momeni A et al 2011 Hot deformation behavior of austenite in HSLA-100 microalloyed steel Materials Science & Engineering A 528 2158–63

[33] Huang K and Logé R E 2016 A review of dynamic recrystallization phenomena in metallic materials Mater. Des. 111 548–74

[34] Beladi H, Cizek P and Hodgson P D 2009 Dynamic Recrystallization of austenite in Ni-30 pct Fe model alloy: microstructure and texture evolution Metallurgical & Materials Transactions A 40 1175–89