Dynamic recrystallization analysis of reduction pretreatment process by multi-phase field method

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Abstract

The reduction pretreatment (RP) process is an effective method to improve billet quality, and the deformation recrystallization plays an important role in the process. Exploring the RP process parameters, a dynamic recrystallization model of GCr15 steel was established by the phase-field method and physical simulation. The recrystallization kinetics and flow stress curves during hot compression were simulated by using this mode. The effects of deformation parameters and initial grain size on the dynamic recrystallization were investigated. Moreover, by using the results obtained by Finite element method (FEM), dynamic recrystallization during the RP process was investigated though this model. It was found that increasing the deformation temperature, deformation rate and decreasing the initial grain size can promote the dynamic recrystallization kinetics. Large Zener-Hollomon parameters can enhance recrystallized grain refinement, while the recrystallized grain size was not affected by the initial grain size. During the RP process, when the reduction is insufficient (10%), partial recrystallization occurs in the billet. With the increase of reduction from 10% to 16%, the area of complete recrystallization increases gradually. When the reduction is the same, the recrystallization in the billet center increases with the decrease of casting speed. When the reduction is 10%, partial recrystallization occurs in the billet center at a casting speed of 0.7 m min⁻¹, and fully recrystallization occurs in the billet center with a casting speed of 0.5 m min⁻¹. Thus, when the reduction is difficult to increase further, the recrystallization in the billet center can be improved by decreasing the casting speed.

1. Introduction

In recent years, the improvement of steel quality has put forward with higher request on the core quality of billet. A great number of researches have been conducted to explore the slab casting under high temperatures and large reductions, including the NS Bloom Large Reduction [1], Porosity Control of Casting Slab (PCCS) [2], Segment under Heavy Reduction [3], Heavy Reduction on Final Solidifying End (HRFSE) [4], the reduction pretreatment (RP) process [5, 6], etc. All the above techniques are known with the characteristics of high thermal deformation temperature, heavy reduction, and low strain rate (0.001 ~ 0.1 s⁻¹). Compared with other mentioned techniques, the RP can be applied after solidification with lower deformation temperature (950 ~ 1250°C). In addition, the proposed technique does not conflict with other techniques for slab quality improvement, which further enhances the core quality of the slab. Given that the processing parameters of the RP process are quite different from the common soft reduction and hot rolling techniques, the study of hot deformation of metals under the RP process is rarely reported. As a common phenomenon during thermal deformation of low stacking fault energy metals [7], dynamic recrystallization could reduce the deformation resistance and has a very important impact on the matrix structure after deformation. Therefore, it is necessary to study the dynamic
recrystallization process to understand the deformation mechanism of metal at high temperature, establish high-temperature constitutive equations, and optimize process parameters.

Mesoscopic simulation methods, such as the cellular automata (CA) method [8–10], the Monte Carlo (MC) method [11–13], and the multiphase field method, are widely used in dynamic recrystallization simulation. Ding and Guo [8] developed a CA model that simulates the microstructural evolution and plastic flow behavior during DRX by coupling the evolution equation of dislocation density. The model was used to simulate the dynamic recrystallization behavior of pure copper, and the effects of various process parameters on the flow stress curve and recrystallization structure were studied. Zhang et al [9] studied the effect of δ phase on dynamic recrystallization of Inconel 718 using CA model. The model shows high accuracy, means the CA model can be used to study the recrystallization with δ phase. The simulation results show that the presence of fine δ phase can refine the recrystallized grains. Zhang et al [10] used experiments and CA models to study the dynamic recrystallization behavior of copper. The results of experiments and simulations show that the CA model can predict the recrystallization rate and grain size very accurately, indicating that the CA model can be used to control the thermal processing process. Peczak and Luton [11] established a dynamic recrystallization MC model by coupling the KM model, this model was used to simulate dynamic recrystallization, and the simulation and experimental results are in good agreement. Hore et al [12] established a multi-scale framework based on the MC method to study the dynamic recrystallization of TRIP steel, and verified the accuracy of the model through comparison with published experimental data. Li et al [13] coupled MC and finite element models to simulate the dynamic recrystallization of tin in tin-rich lead-free solder interconnections during thermal cycling. This study simulates the beneficial role of intermetallic particles in recrystallization and verifies the accuracy of the model by comparing with the experimental results, which proves that the MC method contributes to the reliability research of solder interconnection. The CA method can give a clear physical meaning in simulating the microstructure evolution of materials and has high computational efficiency. However, the CA method has some shortcomings in describing the interface driving and anisotropy, making it difficult to analyze the two-phase interface problems. MC method is simple, fast, and easy to realize the study of two-dimensional and three-dimensional scale. However, due to the probability transformation rule application, it is difficult to establish the corresponding relationship between the calculation time and the real physical time in the MC model. So Takaki et al [14] established an interface field model to simulate dynamic recrystallization. The model is based on the multiphase field model established by Steinbach et al. The migration of the interface is driven by the curvature of the real time domain, so that the evolution of the grains can be accurately reproduced. However, at present, the research of dynamic recrystallization in multiphase field simulation is mostly focused on non-ferrous metals, and its application in steel needs further study.

As a new technology, the RP process is to improve the internal quality of continuous casting billet. Therefore, the process parameters should be matched with the continuous casting process parameters, resulting in a high deformation temperature (1200 °C–1300 °C) and a low deformation rate (0.001–0.1 s⁻¹) in the billet center during the RP process. In this range of deformation conditions, the flow stress curve may appear two situations: multiple peaks and single peak [15]. Compared with the traditional JMAK model, the mesoscopic model has a more explicit physical meaning and is more suitable for dynamic recrystallization under various process parameters [16]. Compared with CA and MC models, the phase-field model does not need to track the two-phase interface in the calculation process, so it is more suitable to deal with interface movement. At the same time, the time and space scale of the phase field model can be determined according to the parameters of the model, so as to achieve the purpose of comparing with the experimental results. Therefore, the phase field model is used to investigate the dynamic recrystallization in present study. This research aims to establish a dynamic recrystallization model with a physical basis, study the recrystallization behavior in the RP process, and provide a theoretical basis for formulating reasonable RP process parameters. In the present study, a dynamic recrystallization model was established based on isothermal compression test and multi-phase field method to analyze the thermal deformation behavior of steel GCr15 at high temperatures. The effects of deformation parameters and initial grain size on the flow stress and recrystallization of steel GCr15 were analyzed. Moreover, the dynamic recrystallization behavior during the RP process was also investigated.

2. Experimental procedure

The experimental material is steel GCr15, and the chemical compositions are shown in table 1. The specimen was machined to a cylindrical shape with a dimension of \( \Phi 10 \times 15 \) mm, and then it was subjected to a single-pass hot compression test using the Gleeble 3800 thermal simulator. According to the Ekelund formula (equation (1)) of average strain rate during the rolling process, the average strain rate of continuous casting slab is 0.007–0.016 when the casting speed is 0.5–0.7 mm min⁻¹, and the reduction is 10%–20%.
\[ \varepsilon = 2v \left( \frac{h_0 - h_1}{R} \right) \]

where \( v \) is the rolling speed, \( h_0 \) is the thickness of plate before rolling, \( h_1 \) is the thickness of plate after rolling, and \( R \) is the roll radius. Therefore, the single pass hot compression experiments were carried out at strain rates of 0.001, 0.01, and 0.1 s\(^{-1}\) with the maximum true strain \( \varepsilon > 0.5 \), followed by rapid cooling to room temperature after compression. Before the compression test, all the specimens were heated up to 1200 °C for 5 min with a heating rate of 10 °C/s, and then were cooled to deformation temperatures of 1000, 1100, and 1200 °C for 20 s with a cooling rate of 10 °C/s to ensure the temperature uniformity. The nickel based high temperature lubricants were used to reduce the friction between the sample and anvil. After deformation, the samples were ground and polished, and then hot corroded with the saturated solution of picric acid. Then the morphology of austenite was observed under optical microscope, and the average grain size of austenite was statistically measured in Image-Pro Plus software by using the linear intercept method. The recrystallized fraction was calculated by the following formula:

\[ X_{\text{dvr.exp}} = \frac{\sigma_{\text{dvr}} - \sigma_{\text{exp}}}{\sigma_{\text{sat}} - \sigma_{\text{ss}}} \]

where \( \sigma_{\text{dvr}} \) is the flow stress if only working hard and dynamic recovery occur in hot deformation, \( \sigma_{\text{exp}} \) is the flow stress obtained in the experiment, \( \sigma_{\text{sat}} \) is the saturation stress, and \( \sigma_{\text{ss}} \) is the steady stress.

### 3. Models

#### 3.1. Phase field model

The phase diagram of GCr15 steel calculated by Thermo-Calc software is shown in figure 1. From figure 1, it can be seen that GCr15 steel is a single-phase multigrain system at the experimental temperature.

In this case, multi-phase method was used to describe the grains in dynamic recrystallization, each phase field variable represents a grain, for example, phase-field variable \( \phi_i \) represents the \( i \)th grain. The free energy of recrystallized material is [14]:

\[ F = \int_V \left[ \sum_{i=1}^{N} \sum_{j=i+1}^{N} \left( -\frac{\alpha_{ij}^2}{2} \nabla \phi_i \cdot \nabla \phi_j + W_{ij} \phi_i \phi_j \right) + f_e \right] dV \]

where \( \alpha_{ij} \) is the gradient coefficient, \( W_{ij} \) is the height of energy barrier, and \( f_e \) is the free energy density in the grains.
The evolution equation of the phase field $\phi_i$ is derived as:

$$\dot{\phi}_i = -\sum_{j=1}^{n} \frac{2M_{ij}^0}{n} \left( \frac{\delta F}{\delta \phi_i} - \frac{\delta F}{\delta \phi_j} \right)$$

(4)

The governing equation for the evolution of phase-field can be expressed as:

$$\frac{\partial \phi_i}{\partial t} = -\sum_{j=1}^{n} \frac{2M_{ij}^0}{n} \left[ \sum_{k=1}^{n} \left\{ (W_k - \bar{W}_k)\phi_k + \frac{1}{2} (a_{ik}^2 - a_{ik}^2) \nabla^2 \phi_k \right\} - \frac{8}{\pi} \sqrt{\phi_i \phi_j} \Delta E_{ij} \right]$$

(5)

where $M_{ij}^0$ is the phase field mobility and $\Delta E_{ij}$ is the difference in stored energy between grains $i$ and $j$, and it can be expressed as:

$$\Delta E_{ij} = \alpha \mu b^2 (\rho_i - \rho_j)$$

(6)

where $\alpha$ is the dislocation interaction coefficient; $\mu$ is the shear modules; $b$ and $\rho$ are Burgers vector and dislocation density, respectively.

$a_{ij}$, $W_{ij}$ and $M_{ij}^0$, are related to the grain boundary thickness $\delta$, grain boundary energy $\gamma_{ij}$ and grain boundary mobility $M_{ij}$, respectively.

$$a_{ij} = \frac{2}{\pi} \sqrt{2b\gamma}$$

(7)

$$W_{ij} = \frac{4\gamma}{\delta}$$

(8)

$$M_{ij}^0 = \frac{\pi^2}{8\delta} M_0$$

(9)

To simplify the model, all the grain boundaries are assumed as large-angle grain boundaries, so $\gamma_{ij} = \gamma_{HAG}$ and $M_{ij} = M_{HAG}$. $\Delta E_{ij}$ is the difference of strain energy storage between grain $i$ and grain $j$,

$$\Delta E_{ij} = \alpha \mu b^2 (\rho_i - \rho_j)$$

(10)

### 3.2. Dynamic recrystallization model

#### 3.2.1. Dislocation evolution

The change of average dislocation density in thermal deformation can be expressed as [17]:

$$\frac{d\rho}{d\varepsilon} = k_1 \rho + \frac{1}{bd} - k_2 \rho$$

(11)

where $d$ represents the average grain size; $k_1$ is a constant and $k_2$ is the softening coefficient which is related to the strain ratio and deformation temperature. $k_1$ and $k_2$ can be calculated by

$$k_1 = \frac{2\theta_0}{\alpha \mu b}$$

(12)

$$k_2 = \frac{\alpha \mu b k_1}{\sigma_{sat}}$$

(13)

where $\theta_0$ is the hardening rate, and $\sigma_{sat} = \{ A_0 \varepsilon \exp (Q_{sat}/RT) \}^{1/\gamma}$ is the saturation stress. Both $\theta_0$ and $\sigma_{sat}$ can be obtained from flow stress curve [18], as shown in figure 2.

#### 3.2.2. Nucleation

Some studies have shown that the nucleation rate of dynamic recrystallization is related to the deformation rate and deformation temperature, so the nucleation equation [8] used in this study is

$$n(\dot{\varepsilon}, T) = C \dot{\varepsilon}^m \exp \left( \frac{Q_n}{RT} \right)$$

(14)

where $C$ and $m$ are constants; $Q_n$ is the activation energy of nucleation; $R$ is the gas constant and $T$ is temperature. Then the volume fraction of dynamic recrystallization can be obtained from

$$\eta = n t_0 \frac{4}{3} r_d^3$$

(15)

where $\eta$ is the volume fraction of dynamic recrystallization; $t$ is time and $r_d$ is the average grain size of dynamic recrystallization. $\eta$ and $r_d$ can be obtained from experiments, and then $n$ can be calculated from equation (15). By using curve fitting, the values of $C$, $m$ and $Q_n$ can be obtained from equation (14).
The critical nucleation dislocation density is calculated by the following formula:

\[ \rho_c = \left( \frac{\sigma_c}{\alpha \mu b} \right)^2 \]  

(16)

where \( \sigma_c \) is critical stress of recrystallization, which can be found in the flow stress curve.

### 3.2.3. Grain boundary mobility

According to the previous study, the grain boundary mobility is related to the grain boundary diffusion coefficient, which can be expressed as [19]:

\[ M = M_0 \exp \left( \frac{Q_b}{RT} \right) \]  

(17)

where \( M_0 \) is the grain boundary diffusion coefficient, and \( Q_b \) is the activation energy for grain boundary diffusion, and their values can be found in the study of Yin et al [20].

### 3.3. Statistics

During the simulation of dynamic recrystallization, the flow stress \( (\sigma) \) [21], average grain size \( (d) \) and recrystallized fraction \( (X_{\text{drx,cal}}) \) can be calculated every certain time interval by using the following equations.

\[ \sigma = \alpha \mu b \sqrt{\bar{\rho}} \]  

(18)

where \( \bar{\rho} \) is the average dislocation density.

\[ \bar{d} = 2 \sqrt{ \frac{S_{\text{Total}}}{\pi N} } \]  

(19)

where \( \bar{d} \) and \( S_{\text{Total}} \) are the average grain size and total area of simulation domain, respectively. \( N \) is the total number of grains in the simulation domain for current time step.

\[ X_{\text{drx,cal}} = \frac{\sigma_{\text{drx}} - \sigma_{\text{cal}}}{\sigma_{\text{sat}} - \sigma_{ss}} \]  

(20)

where \( \sigma_{\text{cal}} \) is the flow stress obtained by the phase field model. It is well known that \( \sigma_{\text{drx}}, \sigma_{\text{sat}} \) and \( \sigma_{ss} \) are usually shown as the function of Zener-Hollomon parameter \( (Z = \dot{\varepsilon} \exp \left( \frac{Q_{\text{act}}}{RT} \right)) \).

### 3.4. Finite element model

The parameters and methods in [22] are used for finite element simulation to obtain the equivalent strain, strain rate, and deformation temperature of the material under the RP process parameters. And use these results as the conditions of the phase-field model to simulate the dynamic recrystallization behavior during the RP process. The simulated billet size is 360 mm × 300 mm × 900 mm, the rolling speed is 0.5, 0.6, and 0.7 m min⁻¹, and the reduction is 10, 12, and 16%.
3.5. Simulation process and parameters

In the dynamic recrystallization simulation using the multiphase field method, the simulation process is shown in figure 3: where \( \varepsilon_{\text{total}} \) is the total strain during simulation.

The parameters used for the simulation are shown in table 2 [20, 23]:

Considering the deformation uniformity of hot compression specimen, the simulation position is in the middle of the hot compression specimen. The program used for calculation is compiled with FORTRAN language and runs on Visual Studio 2017 platform.

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**Table 2. Simulation parameters.**

| Parameter                                      | Value                                                                 |
|------------------------------------------------|----------------------------------------------------------------------|
| Mesh size, \( \Delta x \)                     | 1 (\( \mu \)m)                                                       |
| Grain boundary thickness, \( \delta \)         | 3.5 (\( \mu \)m)                                                     |
| Interfacial energy, \( \gamma \)               | 0.1 (J \cdot m\(^{-2}\))                                             |
| Dislocation interaction coefficient, \( \alpha \)| 0.5                                                                |
| Shear modulus, \( \mu \)                       | 90–0.038 T (GPa)                                                     |
| Burgers vector, \( b \)                        | 0.258 (nm)                                                           |
| Work hardening rate, \( \theta_0 \)            | \(-2.51 T + 4373\) (MPa)                                             |
| Deformation activation energy, \( Q_{\text{act}} \) | 339 (KJ \cdot mol\(^{-1}\))                                        |
| Saturation stress, \( \sigma_{\text{sat}} \)    | 0.295Z\(^{1.1901}\) (MPa)                                            |
| Steady stress, \( \sigma_{\text{ss}} \)         | 0.255Z\(^{1.1901}\) (MPa)                                            |
| Critical stress, \( \sigma_i \)                 | 0.266Z\(^{1.1901}\) (MPa)                                            |
| The nucleation rate formula constant, \( C \)   | 1.1613                                                               |
| The nucleation rate formula constant, \( m \)   | 0.4672                                                               |
| Nucleation activation energy, \( Q_a \)         | 117 (KJ \cdot mol\(^{-1}\))                                         |
| Interface mobility constant, \( M_0 \)          | 1.402 (m\(^{4}\)K \cdot T^{-1}\cdot s\(^{-1}\))                   |
| Initial dislocation density, \( \rho_0 \)      | \( 1 \times 10^6 \) (m\(^{-2}\))                                    |
4. Results and discussion

4.1. Simulation results of hot compression process

The dynamic recrystallization of steel GCr15 was simulated using the hot compression experimental parameters. The calculated flow stress was then compared with the experimental value in order to verify the accuracy of the model. The results of flow stress obtained from the simulation and experiment are shown in Figure 4. It can be seen that the simulation results are in good agreement with the experimental results. It should be noted that when the strain rate is $0.001 \text{ s}^{-1}$, multiple peaks appear on the flow stress curves at $1100^\circ \text{C}$ and $1200^\circ \text{C}$.

Figure 5 shows the variation of dynamic recrystallized fraction with strain. It can be seen that the required strain for dynamic recrystallization decreases with the increase of deformation temperature at the same strain rate. This is because the nucleation rate and the grain boundary mobility are higher, which lead to faster recrystallization at high temperatures [18]. At the same deformation temperature, the strain for recrystallization decreases, with the increase of strain rate, which is associated with the higher nucleation rate.

The microstructures of different process parameters are shown in Figure 6. It can be seen that the recrystallization refines the original microstructure. To quantitatively explain the change of grain size with process parameters, the change of average grain size with $Z$ value is shown in Figure 7. It can be seen from that a higher $Z$ value leads to smaller recrystallized grain size. This is because the recrystallized grain size is affected by the nucleation rate and interfacial mobility. Higher nucleation rate and lower interfacial mobility are beneficial to grain refinement. When $Z$ value is larger, higher strain rate and lower deformation temperature are beneficial to increase the nucleation rate and decrease interfacial mobility. Therefore, the recrystallized grain size is smaller when the $Z$ value is larger.

To evaluate the accuracy of the model, the correlation coefficient (R-square) and root mean square error (RMSE) are used to evaluate the error, the results are shown in Figure 8. From the results, all the R-square is greater than 0.95, and the RMSE is small, indicating that the model has good prediction accuracy.

4.2. Effect of initial grain size

The effect of initial grain size on the flow stress curves, recrystallized fraction and recrystallized grain size are shown in Figure 9. It is found from figures 9(a) and (b) that the dynamic recrystallization kinetics increases with the decrease of grain size before deformation, and therefore the required strain to start recrystallization decreases. The reason is that the decreased initial grain size would increase nucleation sites, leading to an
increased recrystallization kinetics [24]. At the same time, it is known from equation (11) that a decreased grain size enables an increase of dislocation density increasing rate. The required strain to achieve the critical dislocation density thus decreases. In the meantime, with a decrease of the initial grain size, the flow stress curve starts to change from a single peak to a multi-peak. The simulated microstructures of the peak and trough positions of the multi-peak flow stress curve when the initial grain size is 40 microns are shown in figure 10. And the simulated microstructures of the corresponding position of the single peak flow stress curve when the initial grain size is 226 microns are shown in figure 11. The small initial grains promote the recrystallization kinetics, so that the dynamic recrystallization starts quickly and forms the first wave peak, while the dynamic recrystallization starts quickly and forms the first wave peak, while the dynamic recrystallization starts quickly and forms the first wave peak, while the dynamic recrystallization starts quickly and forms the first wave peak, while the dynamic recrystallization starts quickly and forms the first wave peak, while the dynamic recrystallization starts quickly and forms the first wave peak, while the dynamic recrystallization starts quickly and forms the first wave peak, while the dynamic recrystallization starts quickly and forms the first wave peak, while the dynamic recrystallization starts quickly and forms the first wave peak, while the dynamic recrystallization starts quickly and forms the first wave peak.
recrystallization of the sample with large initial grains has not yet started, as shown in figures 10 and 11(b). Subsequently, dynamic recrystallization proceeds rapidly, forming the first trough of the multimodal curve. The deformation is not over, and the dislocation density in the newly formed grains has not reached the critical density of dynamic recrystallization. Therefore, the grains undergo secondary work hardening and get the second peak. With the increase of dislocation density, the second dynamic recrystallization begins, forming a second trough. The dynamic recrystallization occurs on the first dynamic recrystallization grain, as shown in figure 10(c). After several dynamic recrystallization cycles, the recrystallization softening and work hardening reach equilibrium, and the flow stress curve remains at steady stress. In the large initial grain samples, fewer nucleation positions limit the appearance of the recrystallization cycle. After the first recrystallization, the dynamic recrystallization softening and work hardening reach a dynamic balance, and the flow stress curve reaches steady state stress.

It can be seen from figure 9(c) that the recrystallized grain sizes are not affected by the initial grain size. Moreover, the mean grain sizes may increase or decrease once the recrystallization begins, and finally achieve a
steady size. And, the sample with small initial grain size first reaches a steady size. The primary reason is that the density of grain boundaries increases after dynamic recrystallization leads to saturation of nucleation position. At this time, the dominant factors of affecting grain size consist of nucleation rate and mobility. When it comes

Figure 10. Simulated microstructures of DRX (initial grain size: 40 μm): (a) strain: 0, (b) first peak, (c) first trough, (d) second peak, (e) second trough, (f) final microstructure. The blue color represents the deformed matrix while the red is the recrystallized grains.

Figure 11. Simulated microstructures of DRX (initial grain size: 226 μm): (a) strain: 0, (b) first peak position of 40 μm sample, (c) first trough of 40 μm sample, (d) second peak of 40 μm sample, (e) second trough of 40 μm sample, (f) final microstructure. The blue color represents the deformed matrix while the red is the recrystallized grains.
to the sample with a smaller initial grain size, it is relatively quick to produce saturated nucleation sites due to intrinsic dense grain boundaries.

4.3. Dynamic recrystallization during the RP process

For investigating the dynamic recrystallization during the RP process, the RP process was simulated by Abaqus software. The equivalent strain, strain rate, and temperature obtained from the simulation are used as the parameters of phase-field simulation to simulate the recrystallization behavior during the RP process. The simulation results of FEM are shown in figure 12–15.

The temperature distribution from the surface to the center of the billet is shown in figure 12. It can be seen that there is a temperature gradient from the surface to the center. According to Li et al [25], the temperature gradient can increase the deformation of the billet core and enhance the recrystallization. When the casting speed is 0.6 m min$^{-1}$, the variation of equivalent strain and mean strain rate with thickness is shown in figure 13. The figures show that the equivalent strain and strain rate first increase and then decrease with the thickness. The equivalent strain and strain rate in the center of billet are the lowest, while the maximum equivalent strain and strain rate are located at the position 1/8 thickness away from the surface. It can be seen from figures 14 and 15 that the equivalent strain in the billet center increases with the reduction, while the casting speed has little effect on it. The average strain rate increases with the increase of reduction and casting speed.

From the simulated microstructure of each process parameter (figure 16), it can be clearly seen that the recrystallization changes with the process parameters. As the reduction increases and the casting speed
decreases, the recrystallized fraction increases. When the casting speed is 0.6 m min$^{-1}$, the variation of recrystallized fraction and grain size with thickness is shown in figure 17. It can be seen from that there is no dynamic recrystallization on the billet surface due to the low temperature. The position with the largest equivalent strain and mean strain rate in the billet reaches complete recrystallization under three reduction. When the reduction is small, the equivalent strain and strain rate in the slab are low, and partial recrystallization occurs. With the increase of reduction, the area of partial recrystallization decreases. When the reduction is increased to 16%, recrystallization is complete from 1/8 thickness to the center of billet. The recrystallization grain size is related to the degree of recrystallization. When fully recrystallization occurs, the grain size is smaller.

The variation of recrystallization fraction and grain size with casting speed are shown in figure 18. When the reduction is the same, the recrystallized fraction decreases with the increase of casting speed. This is because when the casting speed is high, although the strain rate in the center of the billet is high, the nucleation rate is also high. However, the deformation time is reduced by high casting speed, resulting in the total nucleation lower than the low casting speed. Finally, the degree of recrystallization is lower than that of low casting speed. This means that in the RP process if it is difficult to continue increasing the reduction, the recrystallization and grain refinement can be improved by decreasing the casting speed appropriately.
Figure 16. Simulated microstructure of the billet core under different process parameters: (a) 0.5 m/min-10%, (b) 0.5 m/min-12%, (c) 0.5 m/min-16%, (d) 0.6 m/min-10%, (e) 0.6 m/min-12%, (f) 0.7 m/min-12%, (g) 0.7 m/min-16%, (h) 0.7 m/min-10%, (i) 0.7 m/min-16%. The blue color represents the deformed matrix while the red is the recrystallized grains.

Figure 17. Change of recrystallized fraction (a) and grain size (b) with thickness at casting speed of 0.6 m min$^{-1}$. 
5. Conclusions

1. A model to simulate the dynamic recrystallization of steel GCr15 was established using the multi-phase field method. The calculated results are in good agreement with the experimental results.

2. The model was used to calculate the effect of initial grain size on dynamic recrystallization kinetics and the recrystallized grain size. It is found that the reduction of initial grain size decreases the time and strain required for dynamic recrystallization. The initial grain size has no effect on the recrystallized grain size, but the matrix with a smaller initial grain size reaches the stable level of deformed grain size earlier.

3. The model was used to simulate the recrystallization during the RP process. It is found that partial recrystallization occurs in the billet when the reduction is insufficient. With the increase of reduction, the area of fully recrystallization increases. When the reduction is difficult to increase further, the recrystallization in the billet center can be improved by decreasing the casting speed.

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References

[1] Takubo M, Matsuoka Y, Miura Y, Higashi H and Kittaka S 2015 Proceedings of 2015 Technical Innovation and Fine Production of Continuous Casting Equipment Conference
[2] Kawamoto M 2011 J. Iron Steel Res. Int. 18 (Supplement 2) 28–35
[3] Yim C H, Won Y M, Park J K and Kwon SH 2012 U.S. Patent 245
[4] Yin F, Hua L, Mao H, Han X, Qian D and Zhang R 2014 Mater Design 55 560–73
[5] Li J, Yu W and Cai Q 2016 J. Mater Process Tech. 227 41–8
[6] Wang Y, Cai Q, Li G and Yu W 2017 Steel Res. Int. 88 1603
[7] Salooji A, Dadkhah M, Pavese M, Manfredi D, Biamino S and Fino P 2017 Mat. Sci. Eng. A.-Struct. 696 566–73
[8] Ding R and Guo Z X 2001 Acta Mater 49 3163–75
[9] Zhang H, Liu D, Yang Y, Liu C, Wang J, Zhang Z and Wang H 2020 J. Alloy Compd. 830 154590
[10] Zhang H, Wang J, Chen Q, Shu D, Wang C, Chen G and Zhao Z 2019 J. Alloy Compd. 784 1071–83
[11] Peczak PA 1995 Acta Mater 43 1279–91
[12] Hore S, Das S K, Banerjee S and Mukherjee S 2013 Acta Mater 61 7251–9
[13] Li J, Xu H, Mattila T T, Kivilähti J K, Laurila T and Paulasto-Kröckel M 2010 Comp. Mater. Sci. 50 690–7
[14] Takaki T, Hiroichi T, Hisakuni Y, Yamanaka A and Tornita Y 2008 Mater Trans. 49 2559–65
[15] Sakai T and Jonas J 1984 Acta Mater 32 189–209
[16] Xiong N, Hodgson P, Rolfe B and Li D 2018 Comp. Mater. Sci. 155 299–311
[17] Estrin Y 1996 Unified Constitutive Laws of Plastic Deformation (New York City: Academic Press) 69–106
[18] Haghdadi N, Martin D and Hodgson P 2016 Mater Design 106 420–7
[19] Takaki T, Hisakuni Y, Hiroichi T, Yamanaka A and Tornita Y 2009 Comp. Mater. Sci. 45 881–8
[20] Yin F, Hua L, Mao H, Han X, Qian D and Zhang R 2014 Mater Design 55 560–73
[21] Mecking H and Kocks U F 1981 Acta Mater 29 1863–75
[22] Ning Z, Yu W, Liu H and Cai Q 2020 J. Iron Steel Res. Int. online 1–11
[23] Deng X H, Zhang L W and Yue C X 2009 Mater Res. Innov. 13 436–40
[24] Blaz L, Sakai T and Jonas J 1983 Met. Sci. 17 699–16
[25] Wei Y, Gaosheng L and Qingwu C 2013 Mater Manuf. Process 30 104–10

Figure 18. Change of recrystallized fraction and grain size with casting speed at different reduction: (a) 10%, (b) 12%, (c) 16%.