Recrystallization Kinetics of Fe-3%Si after Deformation at High Strain Rate and High Temperature

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Abstract

Recrystallization kinetics of Fe-3%Si with initial grain size 296–839 µm at the temperature range 1223–1423 K, strain range from 0.51 to 0.92, strain rate range 5–80 s⁻¹ was studied by isothermal compression test using Gleeble-2000. The effect of strain, strain rate, initial grain size and annealing temperature on the recrystallization kinetics were discussed. Avrami equation was used to describe the static recrystallization kinetics. Moreover, the effect of initial grain size and annealing temperature on the exponent in Avrami equation was discussed and the reason of the exponent deviating from the theory value is owed to the effect of static recovery. In all the experimental range the static recrystallization kinetics can be well predicted by Avrami equation.

Keywords: Fe-3%Si, recrystallization kinetics, exponent in avrami equation, prediction.

1. Introduction

As one of the most important soft magnetic materials, grain oriented silicon steel is widely used in electrical industry. Its excellent magnetic property comes from the sharp Goss texture realized by secondary recrystallization. Homogeneous microstructure is the premise for secondary recrystallization taking place, and it needs recrystallization taking place in hot rolling process. On the other hand, grain oriented silicon steel is a ferrite material in high temperature range. The investigation about the static recrystallization kinetics of austenite steel is sufficient and many models have been set up to predict the recrystallization kinetics in the practical production. Although the investigation of static recrystallization about ferrite steel has been carried out early, systematic results have not been obtained. Recently, hot deformation in the ferrite range has been paid attention in the relative lower temperature range, while the investigation of recrystallization in high deformation temperature range is still scarce. Akta et al. have studied the recrystallization behavior of Fe-3%Si steel in the high temperature range from 1173 K to 1373 K and strain rate range from 2.5 to 5 s⁻¹. In the practical production, the strain rate is high in the range from 1 to 120 s⁻¹ and the deformation temperature is in the range 1123 K to 1473 K. With the increase of deformation strain rate and annealing temperature, the kinetics of static recrystallization will be accelerated. For predicting the recrystallization kinetics in the practice, the static recrystallization kinetics in higher strain rate range at relative high temperature needs to be further discussed.

The aim of present paper is to pay attention to the static recrystallization kinetics of Fe-3%Si after deformation at high strain rate and temperature by Gleeble-2000. The effects of initial grain size, strain, strain rate and annealing temperature on the recrystallization kinetics were discussed. Consequently, Avrami Equation was used to regress and predict the recrystallization kinetics in the present experimental range.

2. Material and Experimental

Fe-3%Si alloy used in the present experiment was melted with induction furnace and cast into cylindrical ingot with the chemical compositions (wt.%) of 3.06 Si, 0.015 C, 0.024 Mn, 0.006 S, 0.008 P, 0.01 Cu, 0.01 Al, 0.02 Ni, 0.03 Cr and bal. Fe. The ingot was first homogenized at 1473 K for 1 h, then hot forged to square billet and further hot rolled to sheets with thickness of 20 mm. To obtain medium size grains, the sheet was normalized at 1423 K for 10 min. For obtaining the smaller size grain, the sheet was further rolled to 12 mm at 873 K and normalized at 1423 K for 10 min. For obtaining the larger size grain, the sheet was normalized at 1523 K for 20 min. After that the sheets were cut into cylindrical specimens with diameter of 10 mm and height of 15 mm.

Hot deformation test was carried out on Gleeble-2000 thermo-simulation machine in the temperature range from 1223 K to 1423 K and strain rate range from 5 s⁻¹ to 80 s⁻¹. Two end surfaces of specimen were painted with graphite sheet to reduce the friction between specimen and crosshead. During compression, each specimen was heated to the deformation temperature at 10 K/s and then held for 90 s to eliminate any thermal gradient. After a reduction of 40% or 60%, the specimen...
was held for a given time at the deformation temperature isothermally, then rapidly quenched with water controlled by computer. Compression test was performed in argon atmosphere to prevent oxidation. Quenched specimens were sectioned parallel to the compression axis for metallographic analysis and the point count method\(^\text{14}\) was used to calculate the recrystallization fraction.

### 3. Results and Discussion

#### 3.1. Microstructure and Static recrystallization kinetics curves

Microstructure of deformed samples were analyzed by optical microscopy. The typical microstructure were shown in Fig. 1 corresponds to samples of different annealing time after deformation with strain 0.92 at the strain rate 30s\(^{-1}\) and temperature 1323K. From Fig. 1(a), it can be seen that the grain boundaries especially the edge or corner are the preferential nucleation sites, and the recrystallization was controlled by the grain growth as shown in Fig. 1 (b) and (c). The recrystallization fractions corresponding to different conditions are shown in Fig. 2 with symbols.

From the experimental results shown in Fig. 2, it can be seen that the kinetics of static recrystallization in the experiment range show the typical sigmoid shape which indicate that the kinetics of static recrystallization isothermally can be described by Avrami Equation\(^\text{15}\) that is usually rewritten as\(^\text{1,5,16}\).

\[
X_{\text{rec}} = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^{k}\right]
\]  

(2)

In which, \(t_{0.5}\) is the time used for half recrystallization fraction. Eq.(2) was used to fit the experimental results, and the best fitting lines was also shown in Fig. 2. The values of \(t_{0.5}\) and \(k\) corresponding to different experimental condition were obtained and shown in Table 1, from which it can be seen that the value of \(k\) is obviously affected by initial grain size and annealing temperature, while the strain and strain rate have little effect. According to the theory of Avrami, the value of \(k\) is affected by the growth dimensionality of the recrystallized nucleus when the growth rate keeps constant and the nucleation rate is constant or the nucleation is completed due to the higher nucleation rate in the recrystallization processing. The value of \(k\) is shown in the following table.

![Figure 1. Microstructure of Fe-3%Si steel after deformation with the strain of 0.92 at the strain rate 30s\(^{-1}\) and temperature of 1323K and annealed with time (a) 1s (X\(_{\text{rec}}\) =2%); (b) 5s (X\(_{\text{rec}}\) =51%); (c) 10s (X\(_{\text{rec}}\) =77%); (d) 100s (X\(_{\text{rec}}\) =100%).](image-url)
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Figure 2. Effect of initial grain size (a), strain rate (b), strain (c) and temperature (d) on the kinetics of recrystallization. (a) \(d_0=520\,\mu\text{m}, \varepsilon=0.92, T_{\text{ex}}=1223\,\text{K}\); (b) \(d_0=520\,\mu\text{m}, \varepsilon=30\,\text{s}^{-1}, T_{\text{ex}}=1323\,\text{K}\); (c) \(\varepsilon=0.92, \varepsilon=30\,\text{s}^{-1}, T_{\text{ex}}=1323\,\text{K}\); (d) \(d_0=520\,\mu\text{m}, \varepsilon=0.92\).

Table 1. Regression results for time to 50% recrystallization and \(k\) in Avrami equation.

| \(d_0\) (\(\mu\text{m}\)) | \(\varepsilon\) | \(\varepsilon\)\('\) (\(\text{s}^{-1}\)) | \(T\) (\(\text{K}\)) | \(t_{0.5}\) (s) | \(k\) |
|---|---|---|---|---|---|
| 520 | 0.92 | 5 | 1223 | 83 | 0.89 |
| 520 | 0.92 | 30 | 1323 | 5.2 | 1.20 |
| 520 | 0.92 | 30 | 1423 | 1.6 | 1.75 |
| 296 | 0.92 | 30 | 1323 | 2.4 | 2.00 |
| 839 | 0.92 | 30 | 1323 | 15 | 0.97 |
| 520 | 0.51 | 30 | 1323 | 50.6 | 1.20 |
| 520 | 0.92 | 80 | 1223 | 30 | 0.93 |

Table 2. Ideal exponents in Avrami equation.

| Growth dimensionality | Constant nucleation rate | Nucleation is over |
|---|---|---|
| 1-D | 4 | 3 |
| 2-D | 3 | 2 |
| 3-D | 2 | 1 |

in Table 2 with different growth dimensionality. Cahn\(^{17}\) has extended the theory of Avrami to nucleation on different sites and made a conclusion that if the nucleation is over in the early stage of recrystallization, the value of \(k\) is 1, 2 and 3 corresponding to the nucleation on grain boundary, grain edge and grain corner.

According to the theory of Avrami and Cahn, \(t_{0.5}\) is a function of the grain growth rate. If the growth dimensionality and the grain growth rate were kept constant during the recrystallization processing, the value of \(k\) should be kept constant. In fact, continuous varying of \(t_{0.5}\) in the recrystallization processing due to the effect of other factors including recovery, dynamic recrystallization\(^{18,19}\), precipitation\(^{19-21}\) also change the value of \(k\) when using Avrami equation to regress the experimental results. For example, if the static recovery occurs prior to static recrystallization which decreases the deformation energy of unrecrystallization region, the grain growth rate would be decreased and the time corresponding to the half recrystallization is prolonged, as shown schematically in Fig. 3.

The best fitting lines for part and whole the experimental results were signed with dot and solid lines which were found in aluminium alloy, copper\(^{22}\) and iron\(^{18}\). Humphreys and Hatherly considers that Avrami equation is too simple to quantitatively model the complex recrystallization process. In other words, Avrami equation can be used to model the recrystallization to satisfy the need of practical production, though the physical significance of \(k\) will be different to that proposed by Avrami originally.
3.2. Prediction of recrystallization kinetics

The time for half recrystallization fraction can be affected by the initial grain size \(d_0\), strain \(\varepsilon\), strain rate \(\dot{\varepsilon}\) and annealing temperature \(T\), so the time for half recrystallization \(t_{0.5}\) can be expressed as Eq. (3)\(^{5-7}\):

\[
t_{0.5} = A d_0^l \varepsilon^m \dot{\varepsilon}^n \exp\left(\frac{Q_{\text{rex}}}{RT}\right)
\]

Where \(A, l, m\) and \(n\) are material dependent constants, \(R\) has its usual meaning, and \(Q_{\text{rex}}\) is the apparent activation energy for recrystallization. Take nature logarithm, Eq.(3) can be written as:

\[
\ln(t_{0.5}) = \ln(A) + l \ln(d_0) + m \ln(\varepsilon) + n \ln(\dot{\varepsilon}) + \frac{Q_{\text{rex}}}{RT}
\]

The relationship between the time for half recrystallization fraction and the inverse of annealing temperature is shown in Fig. 4, obviously, it has an approximately linear relationship.

By multivariate linear regress, the constants in Eq.(4) can be obtained as \(A = 6.5 \times 10^{-14}, l = 1.76, m = -3.47, n = -0.38\) and \(Q_{\text{rex}} = 243.6\) kJ/mol. The static recrystallization activation energy is only slightly higher than 230 kJ/mol reported by Akta et al. for Fe-3%Si steel in the temperature range from 1173K to 1373K\(^{13}\), close to the self-diffusion activation energy of 239.3 kJ/mol in high-purity iron\(^{23}\) and higher than the self-diffusion activation energy of Fe atom in Fe-3%Si alloy ranging from 218 kJ/mol\(^{24}\) to 220kJ/mol\(^{25}\).

As discussed above, the value of \(k\) is dependent on the initial grain size and annealing temperature. It is almost independent on the strain and strain rate in the experiment range. Accordingly, the value of \(k\) can be expressed as follows:

\[
k = B d_0^l \varepsilon^m \dot{\varepsilon}^n \exp\left(\frac{Q_k}{RT}\right)
\]
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