Study on high temperature deformation behaviour of GCr15 bearing steel

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Abstract. The high temperature rheological curves of GCr15 bearing steel at different temperatures and strain rates were studied by MMS-300 thermal simulator. The dynamic recrystallization behaviour of GCr15 steel was analyzed with metallographic microscope. The dynamic recrystallization behavior of GCr15 steel was analyzed by combining metallographic microscope. The effects of austenitizing temperature, deformation amount, and strain rate on the dynamic recrystallization of tested steel were systematically studied. Based on this, the equation of hot working is established, and it is pointed out that the activation energy of hot deformation of GCr15 bearing steel is 291.35 kJ/mol.

1. Introduction
Austenite undergoes three physical metallurgical phenomena such as work hardening, dynamic recovery and dynamic recrystallization during the thermal deformation process. The three processes determine the microstructure and deformation resistance of the deformed austenite, and the microstructure and properties of the final material [1]. During the interstitial time after thermal deformation, some of the dynamic recrystallization will undergo sub-dynamic recovery and sub-dynamic recrystallization, then, some of the structures without dynamic recrystallization will undergo static recovery and static recrystallization. These will directly affect the properties of the material after thermal deformation. Therefore, it is necessary to study the high temperature deformation behaviour of tested steel by thermal simulation method, so as to analyse the change law of austenite, adjust the austenite state by controlling hot rolling, and obtain the required structure and properties [2-4].

2. Experimental materials and methods
The experimental material is from ø8mm GCr15 bearing steel wire produced by a company. The main chemical composition (mass fraction, %) is: C 1.0, Cr 1.46, Mn 0.31, Si 0.24, S 0.05, P 0.007, Ti 0.0023, balance Fe.

The MMS-300 thermal simulation test machine was used to compress the sample in a single pass, record the load stroke data, and the stress-strain curves were obtained. The deformation temperatures were selected as 800, 850, 900, 950, 1000, 1050, 1100, and 1150°C, respectively. The deformation rates were 0.01, 0.1, 1, 5, and 10s⁻¹, respectively, and the deformation amount was 0.6. The quenched samples
after the thermal simulation test were cut along the axial direction near the thermocouple joint. After grinding and polishing, they were etched with supersaturated picric acid detergent solution at 75-85°C for 60s. The microstructure was observed by a LEICAQ550IW optical microscope.

3. Experimental results and analysis

3.1. Stress-strain curves

Figure 1. True stress-strain curves of investigated steel at different strain rates and temperatures

Figure 1 shows the true stress-strain curves of investigated steel at different deformation temperatures and strain rates after single pass compressing. It can be seen that when the strain rate is 0.01s⁻¹ and 0.1s⁻¹, and the deformation temperature is 800–1150°C, true stress rapidly increases and reaches a certain peak with the increase of deformation amount at the initial stage of deformation. In the subsequent deformation process, the true stress decreases with the increase of the deformation amount, and gradually reaches a stable rheological state, which indicates that the investigated steel undergoes dynamic recrystallization during the deformation process. However, the true stress reaches a peak and then enters a stable rheological state, when the strain rate is 1s⁻¹ and 10s⁻¹ with the same deformation temperature. It indicates that the softening of the tested steel is mainly based on dynamic recovery. It can also be seen from the curves that under the condition of a certain deformation temperature, when the strain value is constant, the stress peak shifts toward the strain increase direction with the increase of strain rate, which indicates that austenite is not susceptible to dynamic recrystallization as the strain
rate increases. It is because the larger the strain rate, the greater the driving force for recrystallization, and the work hardening also increases with the increase of the strain rate, so that both the peak stress and the peak strain at the time when the effects of recrystallization softening and work hardening are balanced with each other are increased.

3.2. Microstructure

![Microstructures without deforming and with deforming at different strain rates at 1000°C](image)

Figure 2. Microstructures without deforming and with deforming at different strain rates at 1000°C

Figure 2 shows the microstructures of the tested specimens at 1000°C without deformation and deformation at different strain rates. As shown in Fig. 2 (a), the austenite is equiaxed before the thermal deformation, the grain boundary is straight, and the average grain diameter is 237.2 μm. However, when the strain rate is 0.01s⁻¹ and 0.1s⁻¹, the tested steel undergoes complete dynamic recrystallization, and the grain size decreases with the increase of strain rate, as shown in Fig. 2 (b) and (c). This is mainly because the larger the strain rate, the greater the work hardening rate, the higher the dislocation density, and the higher the work hardening and deformation storage energy at the same deformation which can provides greater power for austenite recrystallization. At the same time, after the strain rate is increased, the deformation time will be less, the austenite recrystallization time will be reduced, and the deformed austenite grains will not have sufficient time to recover and grow. When the strain rate is 1s⁻¹, the tested steel undergoes partial dynamic recrystallization. The fine recrystallized grains are distributed on the flattened and elongated austenite grain boundary, and the mixed crystal phenomenon appears according to Fig. 2 (d). This is because the greater the strain rate, the harder it is to carry out dynamic recrystallization. The recrystallization is only 12.3%, and the recrystallization softening does not exceed the work hardening ability. Therefore, the true stress-strain curve of the tested steel exhibits a dynamic recovery type, when the strain rate is greater than or equal that strain rate.

3.3. Thermal processing equation

From the results of the true stress-strain curves of the tested steel, the lower the deformation temperature or the higher the strain rate, the larger the peak stress and the corresponding peak strain, and the harder it is to recrystallize. This relationship can be expressed by the Zener-Hollomon factor [5]:

\[
\dot{\varepsilon} = Z e^{m} \text{exponent}
\]
\[ Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right) \]  

(1)

Where, \( \dot{\varepsilon} \) - thermal deformation activation energy, reflecting the degree of thermal deformation of the material (KJ·mol\(^{-1}\)). \( R \) - gas constant, \( R = 8.31 \text{ J} / (\text{mol} \cdot \text{K}) \). \( T \) - the absolute temperature (K) of thermal deformation. \( Z \) denotes the factor of temperature compensating for deformation rate. When the deformation temperature is lower and the rate is larger, the larger the \( Z \), the larger the deformation amount occurring dynamic recrystallization and the deformation amount after dynamic recrystallization is completed. That is to say, a large amount of deformation is required to cause dynamic recrystallization. The relationship between the \( Z \) factor and the peak stress of deformation is [6]:

\[ Z = A \left[ \sinh (\alpha \sigma_p) \right]^n \]  

(2)

Where, \( A \) - constant, \( \alpha \) - stress factor, generally taken \( \alpha = 0.012 \), \( \sigma_p \) - peak stress, \( n \) - stress index. From Eq.(1) and (2):

\[ \dot{\varepsilon} = A \left[ \sinh (\alpha \sigma_p) \right]^n \exp \left( - \frac{Q}{RT} \right) \]  

(3)

Taking the logarithm of both sides of equation (3) and partial differentiation can be obtained:

\[ \frac{\partial}{\partial \ln \dot{\varepsilon}} \left[ \ln \sinh (\alpha \sigma_p) \right] = \frac{1}{n} \dot{\varepsilon} \left( \frac{\sigma_p}{nR} \right) \]  

(4)

It can be seen from eq.(4) that under the condition of the same temperature, \( \ln \sinh (\alpha \sigma_p) \) and \( \ln \dot{\varepsilon} \) is linear with the slope of \( 1/n \). Data were collected from the true stress-strain curve of the tested steel were linearly regressed to obtain Fig.3(a), and the average value of \( n \) was found to be 3.624. Under the same strain rate, \( \ln \sinh (\alpha \sigma_p) \) and \( 1/T \) also in a linear relationship, the slope is set to \( b \), then

\[ Q = nRb \]  

(5)

**Figure 3.** Correlations of (a) strain rate and (b) deformation temperature with peak stress

Fig.3 (b) shows the relationship between the peak stress of the tested steel and the deformation temperature. The average value of \( b \) can be determined to be 9.67. Bring \( n \) and \( b \) into eq.(4) to find \( Q = 291.35 \text{ kJ/mol} \). By introducing \( Q \), \( n \), \( \sigma_p \) into eq. (2) under each deformation condition, the average
value of A can be obtained, and A = 2.7 × 10^{13}. Therefore, the hot working equation of the tested steel is:

\[ \dot{\varepsilon} = 2.7 \times 10^{13} \left[ \sinh(\alpha \sigma_p)^{1.624} \right] \exp\left( -\frac{291350}{RT} \right) \] (6)

4. Discussion

It can be seen from the above analysis that the strain rate has a great influence on the dynamic recrystallization of the tested steel. When the strain rate is lower than 1 s^{-1}, the tested steel will have full dynamic recrystallization in the range of deformation true strain 0.6 and deformation temperature of 800–1150°C. Moreover, when \( \dot{\varepsilon} = 0.01–0.1 \) s^{-1} and the deformation temperature is higher than 1000°C, the critical strain is less than 0.1.

In the production of wire, the strain rate of the rough rolling pass is generally less than 10 s^{-1}, the deformation amount is about 25%, and the deformation temperature is higher than 1000°C, so the tested steel is easily completely or partially dynamically recrystallized during rolling. During the medium rolling, pre-finishing and finishing rolling, the deformation amount is less than 20%, the strain rate is very high, even the strain rate in the finishing rolling stage can be as high as 200 s^{-1}. At this time, the tested steel cannot undergo dynamic recrystallization. However, due to the rapid rolling speed and the gap time between the passes less than 1 s, it is difficult for the tested steel to undergo static recovery and softening of static recrystallization, so that the strain can accumulate. When the cumulative strain exceeds the critical limit of dynamic recrystallization, partial dynamic recrystallization can also occur in deformed austenite.

According to the characteristics of the strain rate in the wire rolling process, the rough rolling of the tested steel is in the recrystallization zone, and the medium rolling, pre-finishing and finishing rolling are mainly in the non-recrystallization zone. In the non-recrystallization zone, the tested steel should have a large amount of deformation per pass to increase the deformation bands in the deformed austenite grains, increase the precipitation point of the carbides, and make the precipitation of carbides become dispersed. Therefore, the reduction ratio can be appropriately reduced in the rough rolling stage during the controlled rolling, and it should be increased in the subsequent non-recrystallization zone.

5. Conclusion

(1) When the strain rate is 0.01–0.1 \text{s}^{-1} and the deformation temperature is 800–1150°C, the true stress- strain curves of GCr15 bearing steel are dynamic recrystallization.

(2) When the strain rate is 1–10 \text{s}^{-1} and the deformation temperature is 800–1150°C, the true stress- strain curves of GCr15 bearing steel are a dynamic recovery type.

(3) The thermal deformation activation energy of GCr15 bearing steel is 291.35 kJ/mol.

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