Research and control of network carbide in GCr15 bearing steel

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Abstract
Due to the small amount of transformation during the phase transformation process, it is difficult to determine the phase transition temperature of the proeutectoid cementite in the bearing steel by the expansion method. In this paper, the Gleeble3800 thermal simulator was used to study the phase transformation behavior of GCr15 bearing steel at different cooling rates. Firstly, the phase transformation temperature range of pearlite is about 550 °C ~ 700 °C measured by expansion method. Based on this, the transformation temperature range of proeutectoid cementite is about 700 °C ~ 900 °C studied by metallographic method; The precipitation curve of proeutectoid cementite was supplemented, and the complete continuous cooling phase transition curve (CCT curve) of bearing steel was drawn. On this basis, the scheme of inhibiting the formation of proeutectoid cementite by two-stage cooling process was proposed and discussed, and the finishing cooling temperature was studied, which provides a basis for controlling network carbide in field production.

1. Introduction
Before spheroidizing annealing, the microstructure of GCr15 bearing steel is required to be fine pearlite without network carbide [1]. GCr15 bearing steel is hypereutectoid steel, and during the slow cooling process after rolling, the carbide will precipitate along the grain boundary of austenite and form network structure [2]. The existence of network carbide will increase the brittleness of steel and reduce the service life of bearing [3], which is a prominent problem in the production of bearing steel. However, the transformation temperature of proeutectoid carbide is difficult to be measured by expansion method due to the small amount of transformation in the phase transformation process. In the references [4–10], the precipitation curve of proeutectoid carbide has not been measured when measuring the CCT curve of GCr15 bearing steel.

At present, thermal expansion method is the most commonly used method to determine CCT curve. Different phases in steel often have different structures and different specific volumes. When heated or cooled, the difference in specific heat and expansion coefficient will cause volume change on the expansion curve. And the linear relationship between the amount of expansion and the temperature will be broken and turn. According to the inflection point of the expansion curve, the phase transition temperature of the material can be determined. This method of studying the internal microstructure variation law based on the change in the length of the material is the thermal expansion method. However, for the phase transformation with the small amount of transformation, the change of the expansion curve is not obvious, and the measurement accuracy is reduced. Because metallographic method has the advantages of direct observation and accurate results, it is often used as a supplement and calibration method.

Therefore, in this paper, the temperature range of pearlite phase transformation was determined by expansion method using Gleeble-3800 thermal simulator. Then, on the basis of pearlite transformation starting temperature, the transformation temperature of proeutectoid carbide was measured by metallographic method, and the precipitation curve of the proeutectoid carbide was supplemented, the CCT curve of GCr15 bearing steel
was perfected. And based on the complete CCT curve, the two-stage cooling process was adopted, the finishing cooling temperature were studied, and a reasonable two-stage cooling process was established to provide theoretical basis for obtaining ideal microstructure and properties.

2. Experimental procedure

GCr15 bearing steel is hypereutectoid steel with high carbon and high chromium. During continuous cooling process, its equilibrium phase transformation and crystallization process are shown in figure 1. The bearing steel is in the single-phase austenite zone at high temperature (as shown in (I)). During the subsequent slow cooling process, secondary Fe₃C precipitates firstly from austenite when the temperature is cooled to point 1, and the secondary Fe₃C nucleates and grows at the austenite grain boundary (as shown in (II)). During the cooling process from point 1 to 2, secondary Fe₃C continues to precipitate along the grain boundary. Solute atoms, such as C and Cr, generally diffuse more rapidly along grain boundaries than through the austenite crystal lattice. So, the growth rate of particles at grain boundary is much faster than that of bulk diffusion. As a strong carbide forming element, Cr will replace the Fe element in steel and form (Fe, Cr)₃C alloy carbide. With the growth and accumulation of carbide, they are connected to each other to form a network structure (as shown in (III)). And the C content in austenite matrix changes along ES with the continuous precipitation of carbide. When the temperature decreases to point 2, the C content reaches the eutectoid composition point and the eutectoid reaction will occur to produce pearlite (as shown in (IV)). As the temperature continues to decrease, the over-cooled austenite reaches the pearlite transformation zone (as shown in (V)). The room temperature microstructure is pearlite + M₃C. In the actual transformation process, the supercooling degree of austenite increases with the increase of cooling rate. Therefore, the actual transformation temperature will have different degrees of hysteresis, but the transformation principle is the same. Through the equilibrium diagram of Fe-C, network carbide is inevitably formed in GCr15 bearing steel. However, the cooling transformation of GCr15 bearing steel is often unbalanced in the actual production process. Therefore, it is possible to avoid the carbide zone by changing the cooling rate and cool to a certain temperature to pass through the pearlite transformation zone. To achieve this idea, the CCT curve of GCr15 bearing steel must be first measured.

The experimental material is GCr15 bearing steel bar with a diameter of φ50 mm produced by a steel company. Its chemical composition is shown in table 1, and it was machined to thermal simulation sample as shown in figure 2.

Firstly, the complete CCT curve of GCr15 steel was measured. The samples were heated to 1100 °C at the rate of 10 °C s⁻¹ and austenitized for 5 min, and then cooled to 980 °C at the cooling rate of 5 °C s⁻¹ and kept for 10 s, then single pass compression was carried out at the rate of 1/s and deformed by approximately 40%, then

![Figure 1. Schematic illustration of equilibrium diagram of Fe–C and crystallization.](image-url)

| Table 1. Chemical composition of GCr15 bearing steel (mass%). |
|-----------------|------|------|------|------|------|------|------|
| C               | Cr   | Si   | Mn   | P    | S    | Ni   | Cu   |
| 0.98            | 1.47 | 0.24 | 0.35 | 0.013| 0.001| 0.009| 0.01 |

The experimental material is GCr15 bearing steel bar with a diameter of φ50 mm produced by a steel company. Its chemical composition is shown in table 1, and it was machined to thermal simulation sample as shown in figure 2.
the samples were continuously cooled to room temperature at different cooling rates \((V = 0.5, 1, 2, 3, 5, 8, 10, 15 \text{ °C} \text{s}^{-1})\), the experimental process is shown in figure 3(a), and the schematic diagram for the determination of \(Ac_1\) and \(Accm\) is shown in figure 3(b) On this basis, the precipitation temperature of proeutectoid carbide was determined by metallographic method, the experimental process is shown in figure 3(c). When metallographic method was used, On the basis of the starting temperature of phase transition measured by (a), the approximate value of precipitation temperature of proeutectoid carbide was determined by sampling at intervals of 10 °C.

Secondly, based on the complete CCT curve, the two-stage cooling process was used to study the process parameters such as deformation, finish rolling temperature and finish cooling temperature. The samples were heated to 1100 °C at the rate of 10 °C s\(^{-1}\) and austenitized for 5 min, then the samples were cooled to 980 °C at the cooling rate of 5 °C s\(^{-1}\) and kept for 10 s, the samples were deformed by approximately 40%, and then cooled to 820 °C at the cooling rate of 5 °C s\(^{-1}\) and deformed by approximately 30% at the rate of 1/s, and then cooled to different temperatures \((T = 640, 620, 600, 580 \text{ °C})\) at the cooling rate of 8 °C s\(^{-1}\), finally, cooled slowly to room temperature at the cooling rate of 1 °C s\(^{-1}\), the experimental process is shown in figure 4.
3. Experimental results and discussion

3.1. CCT curve of GCr15 bearing steel (including proeutectoid cementite)

The partial expansion-temperature curve are shown in figure 5. And the expansion-temperature curves were processed by tangent method, and the starting and finishing temperatures of phase transformation at different cooling rates were obtained, as shown in table 2.

The metallographic microstructure of GCr15 bearing steel cooled to room temperature at different cooling rates is shown in figure 6.
Table 2. Phase transition temperature of GCr15 bearing steel at different cooling rates.

| Cooling rates (°C s⁻¹) | Start (°C) | Finish (°C) |
|-------------------------|------------|-------------|
| 0.5                     | 710        | 651         |
| 1                       | 702        | 634         |
| 2                       | 684        | 608         |
| 3                       | 672        | 586         |
| 5                       | 651        | 569         |
| 8                       | 623        | —           |
| 10                      | —          | —           |
Because there are many samples needed at each cooling rate and the precipitation temperature is measured at different cooling rates by metallographic method, a cooling rate is chosen to illustrate. The partially quenching microstructures at the cooling rate of 0.5 $^\circ$Cs$^{-1}$ are shown in figure 7. The figure shows the change process of the proeutectoid carbide from none to existence, from less to more, so that the precipitation temperature of proeutectic carbide can be determined at this cooling rate. When quenched at 910 $^\circ$C the microstructure is all martensite. However, when quenched at 900 $^\circ$C, a small amount of proeutectoid carbide appeared in the microstructure. When the quenching temperature was further reduced to 800 $^\circ$C, obvious semi-network or intermittent network carbide appeared in the structure. Accordingly, when the cooling rate is 0.5 $^\circ$Cs$^{-1}$, the precipitation temperature of the proeutectoid carbide is between about 900 $^\circ$C and 910 $^\circ$C, and the intermediate value is 905 $^\circ$C. Similarly, the precipitation temperature of the proeutectoid carbide at other cooling rates can also be measured, and the results are shown in table 3.

Through the combination of expansion method and metallographic method and the observation of microstructure, the complete CCT curve of GCr15 bearing steel is shown in figure 8. The continuous cooling transformation of GCr15 bearing steel mainly consists of five phase regions: single phase austenite zone, austenite + $M_6C$ zone, austenite + $M_7C$ + pearlite zone, $M_7C$ + pearlite zone and martensite zone. The precipitation temperature range of proeutectic carbide is about 700 $\sim$ 900 $^\circ$C, the critical cooling rate for inhibiting the precipitation of proeutectic carbide is 8 $^\circ$Cs$^{-1}$, and the pearlite phase transformation occurs mainly in the temperature range of 550 $\sim$ 700 $^\circ$C, the critical cooling rate of complete pearlite phase

| Cooling rates ($^\circ$Cs$^{-1}$) | Precipitation temperatures ($^\circ$C) |
|---------------------------------|-------------------------------------|
| 0.5                            | 905                                 |
| 1                              | 875                                 |
| 3                              | 815                                 |
| 5                              | 755                                 |
| 8                              | 705                                 |

Figure 7. Quenching microstructure cooled to different temperatures at 0.5 $^\circ$Cs$^{-1}$.
transformation is 5 °C s⁻¹, and with the increase of cooling rate, both phase transition temperatures decrease, especially when the cooling rate is greater than 3 °C s⁻¹, the precipitation temperature of proeutectic carbide decreased more obviously, and the range of precipitation temperature decreased significantly. And the effect of cooling rate on the precipitation temperature of proeutectoid carbide is obviously greater than that of pearlite phase transformation temperature. When the cooling rate is above 8 °C s⁻¹, over-cooled austenite transforms to martensite in the low temperature region.

### 3.2. Two-stage cooling process

According to the Fe–C phase diagram, in the continuous cooling process of bearing steel, the solubility of C in austenite decreases with the decrease of temperature, and the proeutectic cementite begins to precipitate along the austenite boundary. In this process, the secondary carbide precipitated from over-cooled austenite is mainly accomplished by diffusion process, and the cooling rate has a great effect on the precipitation of secondary carbide. The precipitation amount is not only related to the supersaturation of carbon in austenite, but also closely related to the diffusion coefficients of carbide forming elements such as C and Cr in austenite [11, 12].

The strain energy was loosened and diffusion activation energy is lower at grain boundary for its disorder structure compared with crystal basis. Moreover, solute atoms easily concentrate in grain boundary. For above reasons, the critical nucleation energy obviously dropped. So, carbides preferentially precipitate on the grain boundaries. When carbide precipitate from over-cooled austenite, the diffusion rates of elements such as C and Cr along the grain boundary are much faster than that within grain boundary (the difference is 10²–10³ times), which is the reason why secondary carbide precipitate and form network structure at grain boundary [11].

In summary, when the cooling rate is slow during the continuous cooling process of GCr15 bearing steel, C and Cr in the austenite have sufficient time for long-distance diffusion. And the precipitation temperature of the secondary carbide is increased by deformation, and carbide has sufficient time to precipitate and form serious network [13]. When the cooling rate is increased, the degree of over-cooling can be increased, and the phase transition temperature of carbide is reduced, C and Cr cannot diffuse and avoid the secondary carbide phase region. Therefore, the network carbide cannot be formed [14]. However, when the rapid cooling is used, the network carbide is eliminated, but martensite is formed in the martensite phase region, and the pearlite microstructure is not obtained. In order to obtain the pearlite microstructure without network carbide, the GCr15 steel can be quickly cooled to a certain temperature to avoid the proeutectoid cementite phase zone, and then through the pearlite phase region at a low cooling rate and the pearlite transformation occurs completely by the complete CCT curve. This provides a theoretical basis for the two-stage cooling process, and the process idea is shown in figure 9.

### 3.3. Controlling research

The microstructure obtained by two-stage cooling process is shown in figure 10. The obtained microstructures are dense flocculent pearlite, and the network carbide cannot be observed in the microstructure. A small amount of semi-network carbide can be seen from figures 10(a), (b), and in figures 10(c), (d), the degree of precipitation of secondary carbide is further reduced with the decrease of finish cooling temperature, mainly distributed in the...
form of rods and spots, and a large number of granular carbide precipitate and disperse in pearlite matrix structure, which has basically reached the ideal microstructure required in the production process.

Through the change of the above microstructure, the precipitation degree of the secondary carbide decreases obviously with the decrease of the finish cooling temperature at the same cooling rate. According to the CCT curve, the starting temperature of pearlite phase transformation is about 623 °C at the cooling rate of 8 °C s⁻¹, and has not reached the transformation region at 640 °C. However, the cooling rate is fast and the finish cooling
temperature is low, the diffusion coefficient of C and Cr reduces, and the diffusion time is short, so the precipitation of secondary carbide is greatly reduced [15]. Although the precipitation of carbide is inhibited, the secondary carbide can still accumulate and grow during the slow cooling process, and the carbide will distribute along the pearlite grain boundary in semi-network and rod-like shape. When the finish cooling temperature is reduced, the diffusion coefficient of C and Cr will not only decrease further, but also the diffusion time will be shortened, and the precipitation of secondary carbide will be even less, and finally distributed in pearlite structure in the form of particles.

4. Conclusions

(1) The precipitation temperature range of proeutectic carbide is about 700 °C ~ 900 °C, the critical cooling rate for inhibiting the precipitation of proeutectic carbide is 8 °C s⁻¹, and the pearlite phase transformation temperature range is 550 °C ~ 700 °C, the critical cooling rate of complete pearlite phase transformation is 5 °C s⁻¹, and with the increase of cooling rate, both phase transformation temperature decreases, especially when the cooling rate is greater than 3 °C s⁻¹, the precipitation temperature of proeutectic carbide decreased more obviously, and the range of precipitation temperature decreased significantly.

(2) The precipitation degree of secondary carbide will also be significantly reduced with the decrease of finish cooling temperature, and when the finish cooling temperature drops to 600 °C or below, the amount of secondary carbide precipitated is obviously further inhibited and dispersed in granular form on the dense flocculent pearlite matrix.

(3) The precipitation of network carbide can be effectively inhibited by the two-stage cooling process of GCr15 bearing steel cooled to 600 °C with the cooling rate of 8 °C s⁻¹ after finishing rolling deformation at 820 °C and then slow cooling to room temperature at 1 °C s⁻¹, and the pearlite structure without network carbide required before spheroidizing annealing is obtained.

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