

Article

Effect of Rare Earth Y on Microstructure and Mechanical Properties of High-Carbon Chromium Bearing Steel

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Abstract: The effect of rare earth Y on the microstructure and properties of high-carbon chromium bearing steel in different heat treatment processes has been studied. The microstructure and mechanical properties of the bearing steel under hot rolled, annealed and quenched and tempered conditions were compared and analysed, focusing on the effect of inclusions on fatigue performance. The addition of rare earth Y improves the microstructure, Vickers hardness, tensile strength, impact toughness and fatigue properties of bearing steel. The results show that rare earth Y can refine and spheroidise cementite, make the distribution of cementite more uniform, enhance the strengthening effect of the second phase and reduce the stress concentration caused by the shape of cementite. At the same time, the formation of network cementite is inhibited and the harm to grain boundary is reduced. It also has a refining effect on the grain, and the refined grain can achieve better mechanical properties. In addition, by modifying the oxides and sulphides in the steel, the properties of the steel are also improved, particularly in the quenched and tempered state.

Keywords: rare earth Y element; high carbon chromium bearing steel; inclusions; fatigue



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1. Introduction

Bearing steel material is the most widely used material for precision parts, according to chemical composition, performance and use, and can be divided into six categories: high-carbon chromium bearing steel, chromium-free bearing steel, carburised bearing steel, stainless bearing steel, high-temperature bearing steel and anti-magnetic bearing steel [1]. As a representative of high-carbon chromium bearing steel, GCr15 plays an important role in mechanical engineering. As we all know, it has important applications in the manufacture of mechanical parts such as bearing rings and ball screws [2]. This steel has excellent strength and hardness properties [3], which contribute to the smooth operation of equipment. In addition, it is widely used in various fields such as automotive engines, wind turbines and aerospace equipment due to the extreme working conditions usually encountered by bearing steel [4], such as high temperature and high pressure [5]. GCr15 bearing steel has advantages such as a low cost, simple heat treatment process and superior overall performance. However, in use, bearing steel must have high and uniform hardness, toughness, excellent wear resistance and high fatigue strength [6]. Bearing steel materials often have to undergo several heat treatments and machining processes, and there are a large number of microstructural evolutions, including grain size evolution, dislocation proliferation, annihilation, precipitation, damage and phase transformation, which affect the dimensional stability of the workpiece, dimensional accuracy, toughness, hardness, wear resistance and fatigue properties [1]. Previous studies have shown that

the formation of reticular carbides at austenite grain boundaries can seriously affect the quality of bearing steel [7,8]. Therefore, control of the rolled, cooling and heat treatment processes is essential to improve the microstructural properties of bearing steel, particularly with regard to fatigue performance [9]. A new heat treatment method is to control the carbide size of GCr15 and increase the Vickers hardness by tempering at high temperature under a high magnetic field [10]. Hydrogen makes steel brittle, increasing the tendency to crack and reducing the material's properties; all of this is necessary to avoid diffusible hydrogen or render it innocuous when it does enter the steel [11]. Harmful inclusions affect the performance of bearing steel, so it is necessary to control the distribution, shape and size of inclusions, etc. [12]. In recent years, many scientists have conducted in-depth research to improve the mechanical properties of bearing steel. For example, the final rolled temperature and cooling rate in the heat treatment process are controlled to reduce the formation of mesh carbides at grain boundaries [13,14]. Isothermal tempering produces a bainite + martensite two-phase structure which has a better combination of hardness, tensile strength and impact toughness than conventional quenching and tempering [15]. After the bearing steel is tempered at 530 °C, dislocation recovery is slow and Vickers hardness and tensile strength are improved by dislocation strengthening [16]. Modified quenching heat treatment with different austenitisation processes can be used. The holding temperature of 740 °C (close to $A_{c1} = 750$ °C) makes the carbide and grain size of the steel uniform after quenching and low-temperature tempering, effectively reducing the stress concentration during impact loading, retarding crack growth and increasing impact toughness by 37% [17]. Besides, high-purity bearing steel is developed [18,19]. The process of low alkaline slag refining combined with vacuum carbon deoxidation can achieve TiN inclusion control and improve the cleanliness of GCr15 bearing steel [20], and methods such as ultrasonic shot peening [21–23] and ultrasonic rolling [24] are used to form gradient nanostructured surface layers on bearing steel, which can effectively improve the surface hardness and wear resistance of the steel, and also refine the lath martensite to obtain better mechanical properties. Studies have also been carried out on oxides, sulphides and other non-metallic inclusions in bearing steel [25], as these inclusions can act as stress sources leading to cleavage cracking and significantly affect mechanical properties [26]. Yang et al. [27] produced high-carbon chromium bearing steels with different rare earth contents and found that irregular Al_2O_3 and MnS could be modified to regular rare earth inclusions by the addition of rare earth. When the rare earth content was 0.018%, the transverse impact toughness and isotropy of the bearing steel were improved and the inclusions were smaller and more dispersed. However, as the rare earth content is continuously increased, the inclusion size increases and the inclusion distribution deteriorates. Li et al. [28] used the finite element simulation method to study the stress distribution and fatigue behaviour under the influence of holes near inclusions under different assumptions. Hu et al. [29] proposed a new molecular dynamics modelling method for M50 bearing steel and verified the correctness of the model through nanoindentation experiments, which are conducive to the basic understanding of the mechanical properties of M50 bearing steel.

These studies show that, on the one hand, the optimisation of the heat treatment process is very important for improving the performance of the bearing steel and, on the other hand, the addition of rare earth elements can effectively improve the cleanliness of the steel [27,30]. This is because rare earth elements are highly active and react preferentially with oxygen and sulphur in steel, modifying and refining the inclusions [31,32], thereby improving the overall mechanical properties and prolonging the fatigue life of bearing steel [33]. The addition of rare earths can affect the microstructure of steel, improving tensile strength, impact toughness and other mechanical properties, as well as improving transverse impact strength [30], resulting in smaller and more dispersed inclusions [27,34–36]. In addition to the rare earth elements La and Ce, the rare earth element Y also has the ability to improve the properties of steel. However, the study of the microstructure and mechanical properties of GCr15 bearing steel with rare earth element Y added under different heat treatment conditions is still limited. The addition of the rare earth element Y to the

steel plays a unique role. The influence of inclusions on the fatigue properties of GCr15 bearing steel is discussed. This research can further improve the service life and reliability of bearing steel and has important practical significance. In addition, it extends the scope of existing research and fills the knowledge gap on the addition of rare earth Y in bearing steel, which is expected to provide more reference and guidance for subsequent research.

The innovation of this study is that the microstructures and mechanical properties of GCr15 bearing steel and RE-GCr15 bearing steel have been comprehensively investigated after proper heat treatment and the addition of the rare earth Y trace element. Compared with the addition of mixed rare earth La and Ce to GCr15 bearing steel by Zhao et al. [37], GCr15 and RE-GCr15 under this heat treatment process have a smaller grain size and higher hardness, tensile strength and fatigue strength.

2. Materials and Methods

2.1. Materials and Heat Treatment Processes

The composition of the bearing steel was designed according to the requirements of the national standard GB/T 18254-2016 [38]. We produced two batches of steel, and after hot rolled into steel plates, we took samples at 1/4 distance from the edge for chemical composition testing. Table 1 shows the main chemical composition test results for GCr15 and rare earth GCr15 (hereinafter referred to as RE-GCr15). We then used a resistance furnace (SX2-20-10GC, Yixing Feida Electric Furnace Co., Ltd., Yixing, China) to heat both sets of samples from room temperature to 790 °C at a rate of 150 °C/h and then held at this temperature for 3 h. The samples were then cooled to 710 °C at a rate of 20 °C/h and held at this temperature for 2 h before being air cooled to approximately 650 °C at a rate of 20 °C/h to complete the isothermal spheroidisation annealing process.

Table 1. Chemical compositions of the experimental steels (wt.%).

Steels	C	Si	Mn	Cr	Al	P	S	Y	Fe
ORE	0.95	0.28	0.36	1.56	0.055	0.006	0.001	0	Bal.
RE	0.95	0.27	0.36	1.55	0.050	0.006	0.001	0.013	Bal.

The specimens were then heated from room temperature to 840 °C at a rate of 150 °C/h, held at this temperature for 2 h and then oil quenched according to the specified quenching procedure. Finally, the specimens were heated from room temperature to 170 °C at a rate of 150 °C/h, held at this temperature for 4 h and then air cooled to room temperature to complete the low-temperature tempering process.

This completed the heat treatment processes for the specimens under the hot rolled, annealed and quenched and tempered conditions as shown in Figure 1a,b.

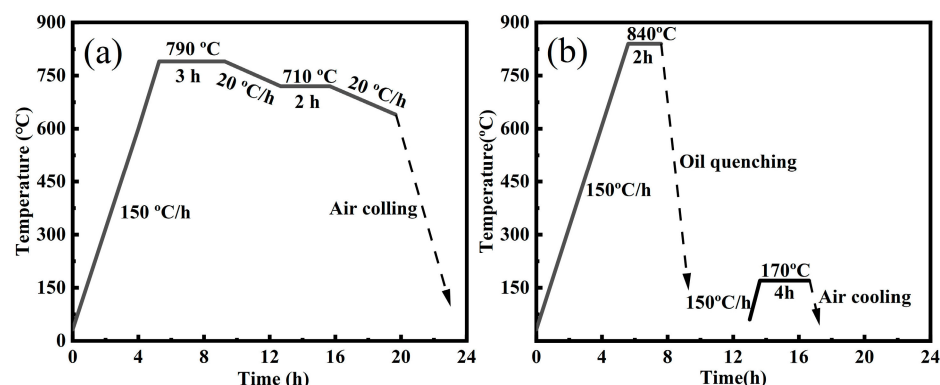


Figure 1. Heat treatment process diagram: (a) isothermal spheroidising annealed and (b) quenched and low-temperature tempered.

2.2. Microstructure Characterization

The microstructure, impact fracture and tensile fracture morphology of GCr15 and RE-GCr15 under different heat treatment conditions were observed and analysed using a Zeiss ZEISS scanning electron microscope (SEM, Carl Zeiss AG, Oberkochen, Germany) and Oxford C-Swift EBSD (Abingdon, Oxfordshire, UK) detector. In the EBSD test, the step size of the hot rolled and annealed specimens was set to 0.2 μm , the raster was 750×750 and the hit rate was over 93%. The step size of the quenched and tempered specimens was set to 0.05 μm , the raster was 700×700 and the hit rate was over 85%. The data processing software Aztec crystal 2.1 was used. The EBSD samples with dimensions of $10 \text{ mm} \times 10 \text{ mm} \times 4 \text{ mm}$ were first polished with SiC abrasive paper with grits ranging from 400 to 2000, then polished with diamond polishing fluid and finally, mechanically polished by vibration. The phase distribution and crystal type of the bearing steel under different heat treatment conditions were analysed by X-ray diffraction (XRD). The specific parameters were Cu K α , scan rate of $8^\circ/\text{min}$, scan angle of $30^\circ \sim 90^\circ$, voltage of 30 kV and current of 30 mA.

2.3. Mechanical Property Test

The microhardness of the specimens was measured on a DuraScan micro Vickers hardness tester using a load of 500 g for a dwell time of 20 s. Random measurements were taken five times in different areas of the specimen to ensure the randomness and accuracy of test data. The tensile test was conducted using a WDW-200D-200KN microcomputer-controlled (Jinan Ding test equipment Co., Ltd., Jinan, China) electronic universal testing machine with a specimen diameter of 5 mm, the standard size (GB/T228.1-2021 [39]), and a strain rate of $1 \times 10^{-3} \text{ s}^{-1}$. The specimen size is shown in Figure 2a. For the impact test, the impact test standard (GB/T229-2020 [40]) was adopted to test 12 groups (3 in each group) of $10 \text{ mm} \times 10 \text{ mm} \times 55 \text{ mm}$ V-notch specimens. The sample size shown in Figure 2b was used to obtain the average impact toughness and to ensure reproducibility. Room temperature fatigue tests were performed on an MTS Landmark370.10 HFP 5100 (MTS, Eden Prairie, MN, USA) fatigue testing machine in accordance with the standard (GB/T 3075-2021 [41]) with specimen dimensions as shown in Figure 2c.

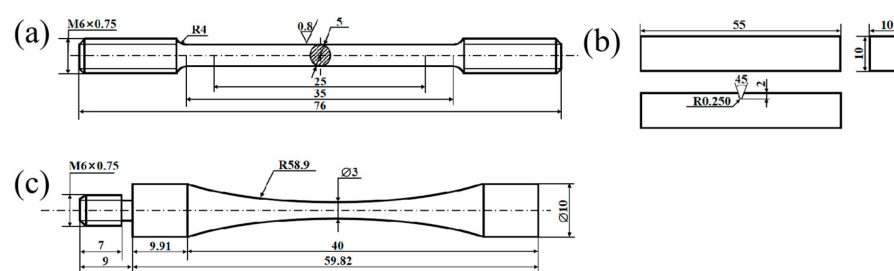


Figure 2. (a) Schematic diagram of tensile specimen size, (b) schematic diagram of impact specimen size and (c) fatigue specimen size diagram (mm).

3. Results and Discussion

3.1. Phase Analysis and Microstructure

Figure 3a,b shows the XRD pattern of GCr15 and RE-GCr15 bearing steel in the hot rolled, annealed and quenched and tempered conditions. It can be seen that the rare earth element Y has little influence on the phase distribution of the bearing steel in the hot rolled and annealed conditions. Unlike what has been reported in the literature [42], a small amount of residual austenite (FCC) was found in the quenched and tempered samples. The residual austenite content was determined by MDI Jade 9 software (V9.0.2@04/16/2009). The residual austenite content of GCr15 bearing steel was 1.8%, and the residual austenite content of RE-GCr15 bearing steel was 3.6%. The residual austenite content increased after the addition of rare earth Y. In the literature [43], it has been pointed out that with the solid solution of rare earth Y atom in steel, the bonding force between γ -Fe cell atoms in the

rare earth atom segregation region in steel would be increased, while the lattice distortion would be increased and the phase structure factor would be increased. These changes could delay the grain boundary nucleation process and improve the stability of supercooled austenite. However, because the amount of rare earth Y is only 130 ppm, the effect on the residual austenite is not so great, demonstrating only a small degree of improvement.

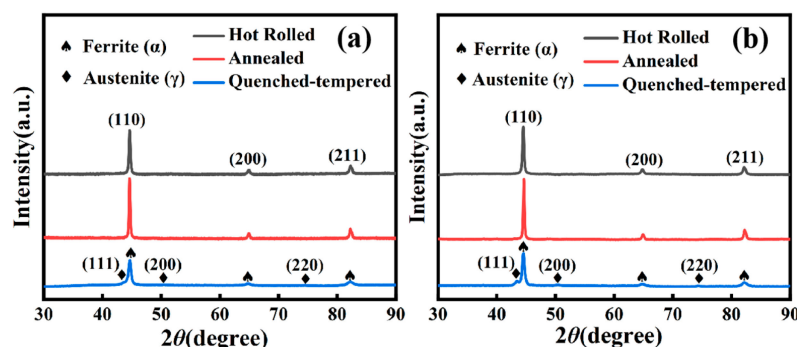


Figure 3. XRD patterns of (a) GCr15 and (b) RE-GCr15 under different heat treatment conditions.

To investigate the influence of microstructure on the properties of GCr15 and RE-GCr15 samples, SEM (scanning electron microscope) was used to observe the microstructure morphology of GCr15 and RE-GCr15 samples. The results showed that in the hot rolled state, both GCr15 and RE-GCr15 samples exhibited a fine lamellar pearlite structure, as shown in Figure 4a,d. After the addition of the rare earth element Y, a continuous growth of long strip carbide occurred near the grain boundary of GCr15, but not at the grain boundary of RE-GCr15 bearing steel, indicating that the addition of the rare earth element Y may inhibit the continuous growth of carbides and thus, hinder the formation of network cementite structure. Hamidzadeh et al. [44] also pointed out in their study that after rare earth modification, since the rare earth oxide sulphide can be used as the heterogeneous nucleus of M_7C_3 eutectic carbide, the nucleation of M_7C_3 eutectic carbide is enhanced, the refinement degree of eutectic carbide is improved, the grain boundary network eutectic carbide is refined and uniformly distributed in the microstructure, and the grain boundary eutectic carbide content is greatly reduced. Therefore, no obvious grain boundary network carbides were found in RE-GCr15 steel. Using Image J software 1.35t, the interlamellar spacing of the pearlite was measured. We found that the average interlamellar spacing of GCr15 was 236.6 nm, while the average interlamellar spacing of RE-GCr15 was 145.6 nm, a reduction of 46.2%. When rare earth was added, the lamellar spacing of the pearlite decreased, which is attributed to the combined effects of stimulating nucleation by a large number of micrometer-scale RE-containing inclusions and decreased carbon diffusion due to RE in solution [45]. The reduction of pearlite lamellar spacing will also increase the strength and hardness of the steel [45,46]. Figure 4b,e are the SEM images after spheroidisation annealing. The average diameter of the granular pearlite GCr15 was 578.5 nm and the volume fraction was 54.41%. The average diameter of the granular pearlite of RE-GCr15 was 666.9 nm and the volume fraction was 47.48%. Figure 4c,f shows the microstructure of the bearing steel after quenching and tempering, both showing a typical tempered martensite matrix with a large number of diffusely distributed carbide particles. The carbide in RE-GCr15 steel was smaller in volume, more dispersed in distribution and finer in microstructure. From a microstructural point of view, RE-GCr15 had better mechanical properties than GCr15.

In addition, the addition of the rare earth Y will affect the grain size of the bearing steel under different heat treatment processes. In the hot rolled state, it can be seen from the IPF (Inverse Pole Figure), Figure 5a,d, and all phase figure, Figure 5b,e, that the grain size was refined after the addition of the rare earth element Y. According to the quantitative analysis in Figure 5c,f, the average grain size was reduced from 8.3 μm to 6.6 μm . After rare earth elements were added to the molten steel, rare earth compounds with a higher

melting point and more dispersed distribution were uniformly distributed in the molten steel, and the heterogeneous nucleation of the molten steel provided the nucleation core, thus refining the grains. In addition, the surface activity of the rare earth was high, and the rare earth solute atoms in the steel were distributed at the grain boundaries, which can reduce the interfacial energy and interfacial tension of the austenite grain boundaries. Thus, the driving force of grain growth was reduced, the required temperature was increased and austenite grain growth was inhibited, and the solidification structure was obviously refined and the carbide distribution became more dispersed and uniform [47], resulting in finer grains. The main purpose of spheroidised annealing is to reduce hardness, facilitate machining and prepare for the final quenching and tempering process. From IPF Figure 6a,d and all phase Figure 6b,e it can be seen that the grain size after annealing is relatively large and there are small grains inside. It can be seen from the quantitative analysis shown in Figure 6c,f that the addition of rare earth Y reduced the average grain size of GCr15 from 17.9 μm to 16.9 μm , and RE-GCr15 tended to form equiaxed or quasi-equiaxed crystals. The quantitative statistical analysis is shown in Figure 7a,b.

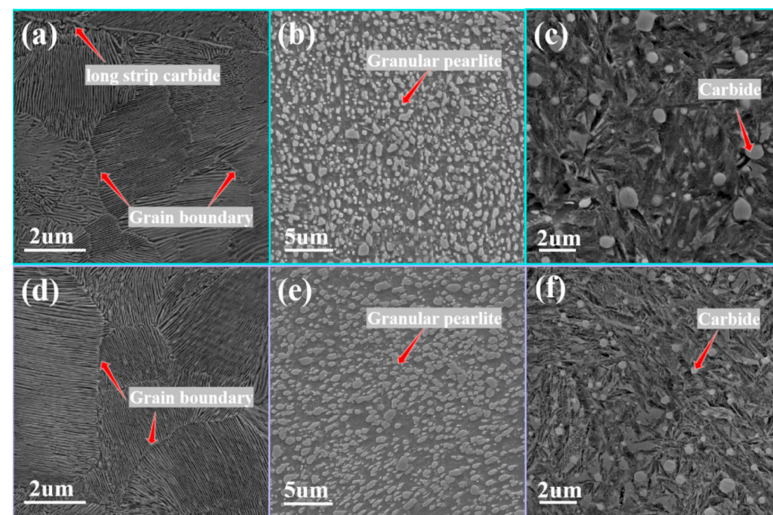


Figure 4. SEM images of (a–c) GCr15 and (d–f) RE-GCr15 under (a,d) hot rolled, (b,e) annealed and (c,f) quenched and tempered conditions.

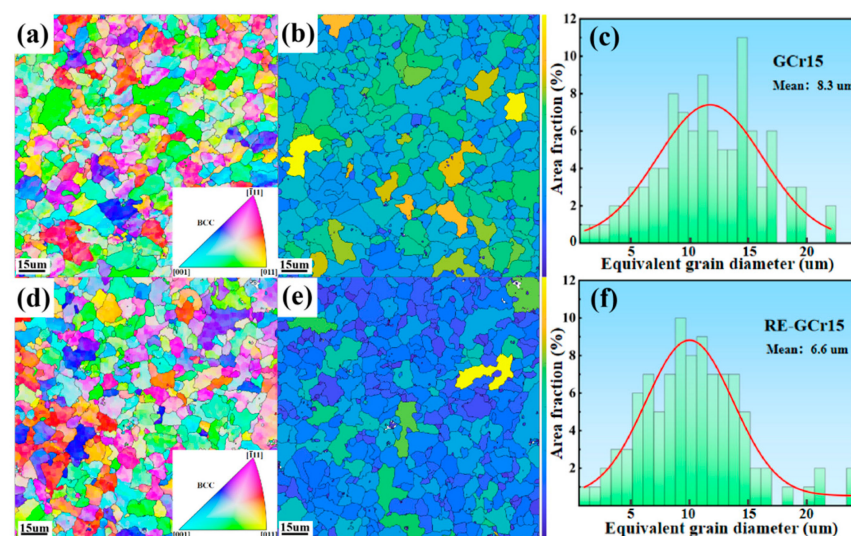


Figure 5. (a,d) IPF, (b,e) all phase figure and (c,f) grain distribution of (a–c) GCr15 and (d–f) RE-GCr15 under the hot rolled condition.

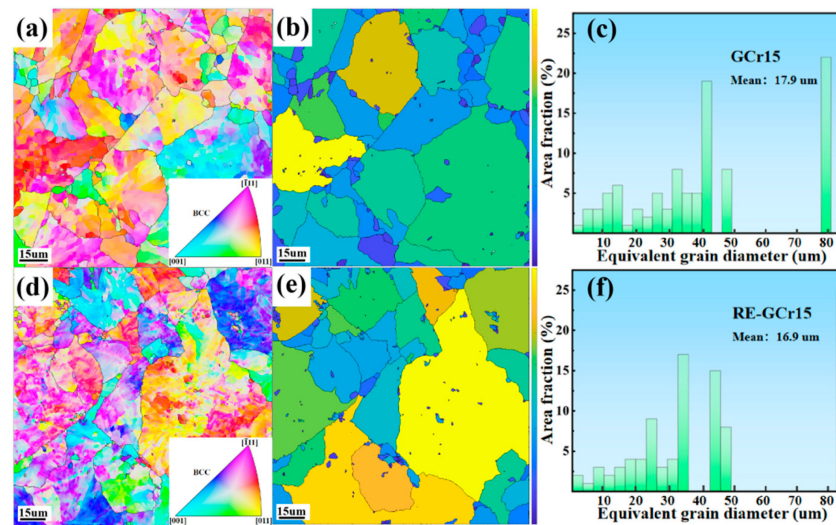


Figure 6. (a,d) IPF, (b,e) all phase figure and (c,f) grain distribution of (a–c) GCr15 and (d–f) RE-GCr15 under the annealed condition.

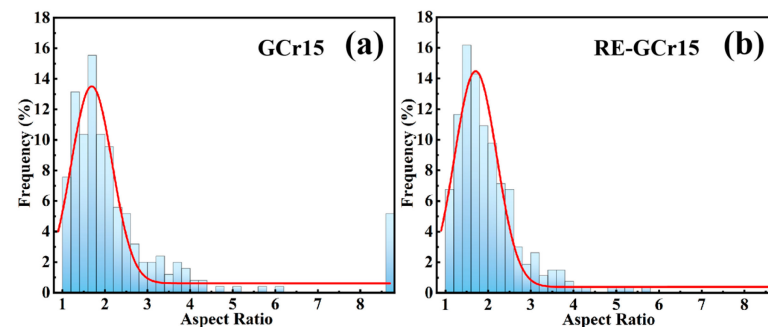


Figure 7. Aspect ratio distribution of (a) GCr15 and (b) RE-GCr15 grains under annealed condition.

The addition of rare earth Y can obviously refine the grain size under quenched and tempered conditions as shown in the IPF, Figure 8a,d, and all phase figure, Figure 8b,e. According to the quantitative analysis in Figure 8c,f, the grain size of GCr15 is reduced from 0.65 μm to 0.43 μm. It can be seen from Figure 9a,c that the size of carbide decreases and the quantity of carbide increases. This is because the addition of rare earth Y can combine with carbon in steel, promote the formation of rare earth carbides in steel and form more small dispersed rare earth carbides. The size distribution of Fe₃C is shown in Figure 9b,d. The average carbide size (at 95% CI, confidence intervals), and the carbide, residual austenite and martensite volume fractions of GCr15 and RE-GCr15 obtained by quantitative analysis are shown in Table 2. The average carbide size decreased from 0.44 μm to 0.38 μm, a reduction of 13.6%, and the carbide fraction increased from 5.2% to 6.3%. The residual austenite content increased from 1.3% to 3.4%, which is roughly consistent with the results calculated by MDI Jade 9 software. The martensite content decreased from 93.5% to 90.3%. The addition of rare earth Y can combine with carbon in steel, promoting the formation of carbonaceous rare earth inclusions in carbon and the formation of more small dispersed carbides. The presence of rare earth Y atoms will affect the diffusion rate of carbon atoms in steel, and then affect the martensite formed by consuming carbon atoms and reduce the content of martensite. At the same time, the decomposition of carbon atoms in austenite is also affected by the rare earth Y atoms, resulting in an increase in the residual austenite content. The distribution of the Fe₃C aspect ratio in GCr15 and RE-GCr15 is shown in Figure 10. Obviously, the number of Fe₃C aspect ratios in RE-GCr15 is closer to 1 than in GCr15, which means that the carbides in RE-GCr15 tended to be more spherical. The spheroidisation of carbides in steel can improve ductility, toughness and machinability and reduce distortion and cracking during the final heat treatment.

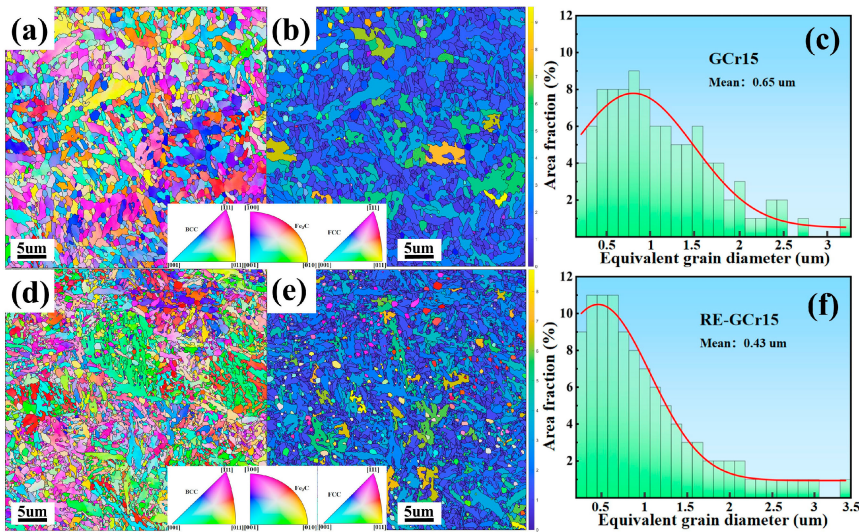


Figure 8. (a,d) IPF, (b,e) all phase figure and (c,f) grain distribution of (a–c) GCr15 and (d–f) RE-GCr15 under the quenched and tempered condition.

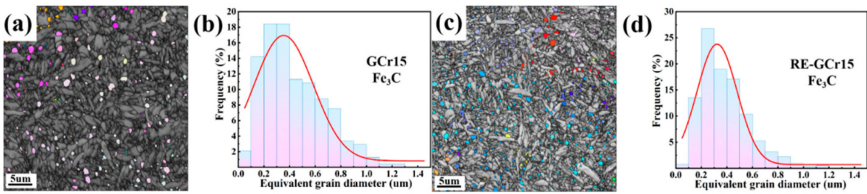


Figure 9. Carbide and carbide particle size distributions of (a,b) GCr15 and (c,d) RE-GCr15 measured by EBSD.

Table 2. Average carbide size (95% CI) and phase fraction of GCr15 and RE-GCr15.

Steels	Average Size of Carbide (μm)	Volume Fraction of Carbide (%)	Volume Fraction of Retained Austenite (%)	Volume Fraction of Martensite (%)
GCr15	0.44 (0.41~0.47)	5.2%	1.3%	93.5%
RE-GCr15	0.38 (0.37~0.40)	6.3%	3.4%	90.3%

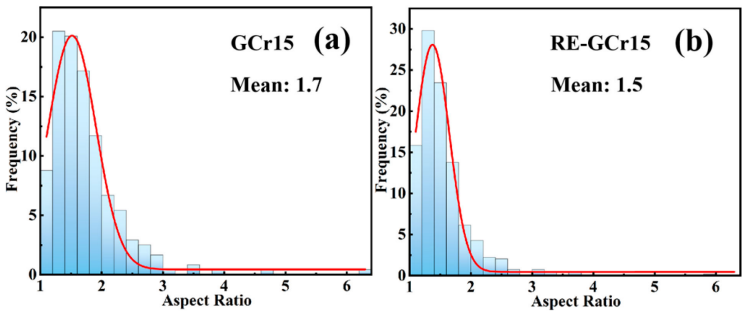


Figure 10. Carbide aspect ratio layout of (a) GCr15 and (b) RE-GCr15.

In summary, rare earth Y had little effect on the phase distribution of GCr15 bearing steel under different heat treatment conditions. The impact on microstructure was mainly manifested in grain refinement. Under hot rolled conditions, the addition of rare earth Y can inhibit the formation of network carbide and reduce the interlayer spacing of pearlite. Under annealed conditions, the grains tended to form equiaxed or quasi-equiaxed crystals. Under quenched and tempered conditions, the distribution of carbides became uniform, the size decreased and the shape tended to be spherical.

3.2. Mechanical Property

It is concluded that the addition of rare earth Y affects the microstructure of bearing steel. According to previous reports, researchers have found that the addition of rare earth Y has a certain impact on the mechanical properties of bearing steel, and this study mainly discusses the changes in hardness, tensile and impact properties of bearing steel after the addition of rare earth Y.

3.2.1. Effect of Rare Earth Y on the Hardness of GCr15 Bearing Steel under Different Heat Treatments

Figure 11 shows the Vickers hardness of GCr15 and RE-GCr15 under different heat treatment conditions. After the addition of the rare earth element Y, the hardness of the hot rolled steel increased by 12.25%. The RE in the solution retards the diffusion of carbon, which decreases the interlamellar spacing of pearlite, resulting in increased hardness [45]. After annealing, the average pearlite cluster size of RE-GCr15 samples increased and the area fraction decreased, so the hardness of RE-GCr15 decreased slightly, which is a better preparation for subsequent machining. The hardness after quenching and tempering increased by 13.58%. Through comparative study, it was found that the contribution of grain size to the hardness value was less than that of the volume fraction of each phase. This is because under the annealed conditions, the grain size of RE-GCr15 was reduced, but the hardness was slightly reduced because the average size of the pearlite group increased and the total area fraction decreased. In the quenched and tempered condition, it is generally accepted that the higher the volume fraction of martensite, the lower the residual austenite and the higher the hardness. Combined with Table 2, it can be seen that the addition of rare earth Y reduced the martensite content and increased the residual austenite content, which is obviously not the main factor in determining hardness. However, the decrease in carbide size, the increase in volume fraction and the more dispersed distribution are the main reasons for the increase in hardness. In addition, studies have shown that the diffusion of rare earth elements in steel can form smaller second phase particles and higher hardness [48]. There are also reports that the segregation, diffusion and precipitation of rare earth elements affect and increase the hardness of steel [49]. In addition, the C content of martensite at seven different locations and residual austenite at seven different locations in GCr15 and RE-GCr15, respectively, were measured by EDS local C content measurement. The results showed that the average atomic proportion of C atoms in residual austenite in GCr15 was $5.96 (\pm 0.6)\%$ and the average atomic proportion of C atoms in residual austenite in RE-GCr15 was $5.88 (\pm 1.4)\%$. After the addition of rare earth Y, the carbon content of the residual austenite in the steel was reduced. The average atomic proportion of C atoms in martensite increased from $7.19 (\pm 1.6)\%$ to $7.71 (\pm 1.4)\%$, and the increase in carbon content in martensite will increase the hardness of the steel.

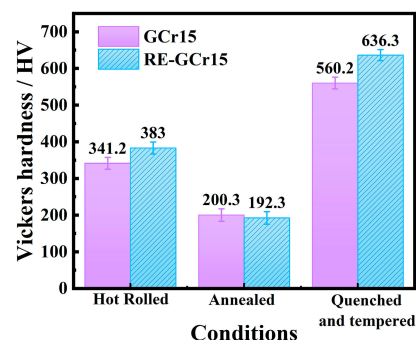


Figure 11. Vickers hardness of GCr15 and RE-GCr15 under different heat treatment conditions.

3.2.2. Effect of Rare Earth Y on the Tensile Properties of GCr15 Bearing Steel under Different Heat Treatments

The effect of rare earth element Y on the properties of GCr15 steel under different heat treatment conditions was studied through room temperature tensile tests. After the

addition of rare earth element Y, the yield strength, tensile strength of GCr15 bearing steel were all improved to varying degrees, calculated using a 95% confidence interval, as shown in Table 3.

Table 3. Tensile properties and 95% CI of GCr15 and RE-GCr15 under different heat treatment conditions.

Heat Treatment Conditions	Yield Limit (MPa)		Tensile Limit (MPa)	
	GCr15	RE-GCr15	GCr15	RE-GCr15
Hot rolled	845	900	1349	1387
	(842~851)	(895~902)	(1347~1351)	(1385~1388)
Annealed	431	431	721	715
	(431~435)	(430~435)	(717~721)	(713~716)
Quenched and tempered	1320	1335	2134	2217
	(1319~1324)	(1328~1342)	(2129~2139)	(2213~2221)

In the hot rolled state, the yield strength of the steel increased from 845 MPa to 900 MPa, and the tensile strength increased from 1349 MPa to 1387 MPa. In the annealed state, the yield strength of both groups of steel was 431 MPa, while the upper yield stress after the addition of the rare earth element Y was 484 MPa. The tensile strength remained basically unchanged. In the quenched and tempered state, the yield limit increased from 1320 MPa to 1335 MPa, and the tensile strength increased from 2134 MPa to 2217 MPa. Figure 12 shows the engineering stress–strain curves of GCr15 and RE-GCr15 bearing steels after hot rolled, annealed and quenched and tempered conditions.

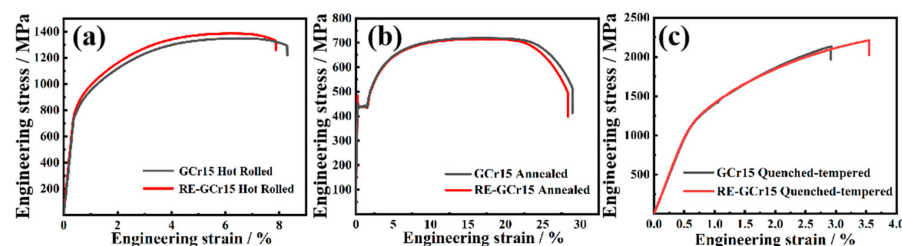


Figure 12. Engineering stress–strain curves of GCr15 and RE-GCr15 bearing steels under (a) hot rolled, (b) annealed and (c) quenched and tempered conditions.

It is well known that fine grain size and uniform phase distribution usually increase the strength and elongation of steel. According to our discussion in Section 3.1, it is known that after rare earth Y addition, the grain size decreases and the carbides are diffusely distributed. In addition, rare earth Y addition leads to the refinement and diffuse distribution of inclusions in steel. Uniform phase distribution helps to enhance the mechanical properties of steel because the interaction between different phases helps to improve the strength and toughness of the material. On the contrary, if there is an uneven phase distribution, some areas may be enriched with a particular phase while other areas are deficient in that phase. This inhomogeneous phase distribution may lead to differences in the mechanical properties of the material, with specific regions exhibiting lower strength and toughness.

The addition of the rare earth element Y significantly improved the tensile strength of bearing steel under hot rolled and quenched and tempered conditions. After the addition of rare earth elements, they may form rare earth inclusions with S and P in steel, which affects the distribution of impurity elements in steel. The segregation of impurity elements such as S and P at grain boundaries is reduced and the grain boundaries are purified [50]. In addition, solute rare earth can enhance the binding force of grain boundaries by segregation at grain boundaries [51], thereby increasing the strength of grain boundaries. The addition of rare earth can refine grain size and improve material strength [52]. Rare earth compound inclusions containing C are formed in steel, which hinders the formation of a network of carbides at grain boundaries and makes the grain boundaries less susceptible to fracture [13].

The phase distribution is more uniform after the addition of rare earth Y. Therefore, the addition of rare earth Y improves the tensile properties of GCr15 bearing steel.

In addition, in order to deeply understand the influence of rare earth Y on the tensile properties of GCr15 steel, the tensile fracture morphology under hot rolled, annealed and quenched and tempered conditions was observed by SEM, as shown in Figure 13. The tensile fracture morphology of GCr15 bearing steel in the hot rolled condition, according to the tensile test, is shown in Figure 13a; the fracture is relatively flat, and the surface of the RE-GCr15 fracture is rougher, as shown in Figure 13b. The fracture surface of GCr15 forms parallel clusters and the crystal faces at different heights form steps with a small number of small dimples on the steps as shown in Figure 13(a₁,a₂). By comparing the area of the cleavage surface on the GCr15 and RE-GCr15 fractures, it was found that the cleavage area on the RE-GCr15 fracture is smaller, indicating that the grain boundary strength of RE-GCr15 is higher, as shown in Figure 13(a₁,b₁). According to the principle of minimum fracture energy consumption, the crack propagation path is always along the surface with the weakest atomic bond; S and P in steel are segregated at grain boundaries, and brittle phases (Al₂O₃, spinel and other types of inclusions) precipitated at grain boundaries can weaken the grain boundaries so that along-crystal fracture occurs [53]. In addition, rare earth sulphides were formed near the crack source as shown by EDS testing, as shown in point 1 and point 2 in Figure 13(b₂). The rare earth element Y is located at the periphery of MnS inclusions. The formation of spherical RE sulphides reduced the segregation of S elements at grain boundaries, reduced the weakening effect of S elements at grain boundaries and improved the strength of grain boundaries so that the fracture area along the grain was less. Both groups of specimens fractured with near brittle fracture.

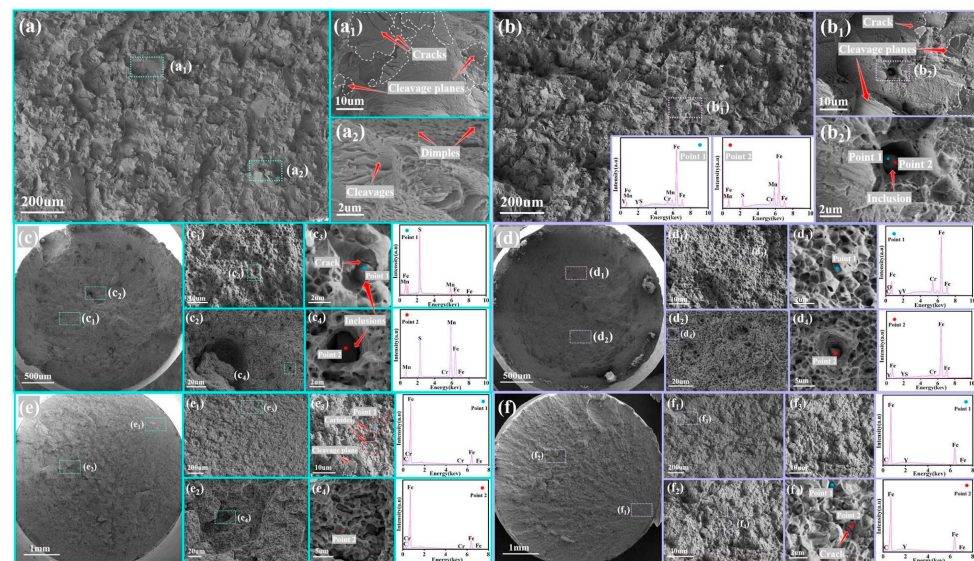


Figure 13. SEM images of tensile fracture morphology: GCr15: (a) hot rolled, (c) annealed, (e) quenched and tempered; (a₁,a₂), (c₁,c₂) and (e₁,e₂) are enlarged graphs of the marked positions in figures a,c and e respectively; (c₃,c₄) and (e₃,e₄) are enlarged graphs of the marked positions in (c₁,c₂) and (e₁,e₂) respectively; RE-GCr15: (b) hot rolled, (d) annealed, (f) quenched and tempered; (b₁,b₂), (d₁,d₂) and (f₁,f₂) are enlarged graphs of the marked positions in figures a,c and e respectively; (d₃,d₄) and (f₃,f₄) are enlarged graphs of the marked positions in (d₁,d₂) and (f₁,f₂) respectively.

The annealed specimens show a clear necking characteristic morphology at the edges, which is the main feature of ductile fracture with high shrinkage. There was no significant difference in the macro fracture morphology between GCr15 and RE-GCr15, as shown in Figure 13c,d. A large number of dimples of different sizes and depths were formed in Figure 13(c₁,c₂) and Figure 13(d₁,d₂), respectively. MnS inclusions existed in the dimples of GCr15 bearing steel, as shown in Figure 13(c₃,c₄). In Figure 13(c₃), the MnS inclusion

was broken at the centre. This promotes crack growth, which reduces the properties of the material. The addition of rare earth Y led to the formation of rare earth oxides and sulphides in the dimple, which have a stronger bonding force and higher upper yield strength, as shown in Figure 13(d₃,d₄).

In Figure 13e,f, the fracture surface is bright, both are brittle fractures with high strength limits, and the fracture source region is a cleavage step with a large difference in depth, as seen in Figure 13(e₁,e₂,f₁,f₂). As can be seen from Figure 13(e₃), the originally complete and smooth deconstructed surface was decomposed into craters formed with multiple single carbides as the core due to the presence of spherical carbides, and the EDS of the carbides is shown in Figure 13(e₃,e₄). The energy consumption of this form of carbide is enormous and prevents the formation of the cleavage surface and cracks in a straight line extension. The rare earth Y elements combine with carbon elements to form rare earth carbides, which have high strength, while the rare earth Y elements can promote grain refinement and the formation of more fine carbides, as shown in Figure 13(f₃,f₄), and the fine carbide particles can provide more sources of reinforcing dislocations and prevent crystal slip and deformation [54]. In addition, the rare earth Y elements form compounds with the carbon elements, thereby reducing the diffusion of the carbon elements in the steel, which prevents the carbon elements from aggregating at the grain boundaries and reduces grain boundary embrittlement. Therefore, RE-GCr15 had higher performance in the quenched and tempered condition.

In summary, the addition of rare earth Y can refine the grain, refine the lamellar pearlite and martensite flakes, and help to improve the yield strength and tensile strength in the hot rolled and quenched and tempered conditions. The addition of rare earth Y has little effect on the yield strength and tensile strength in the annealed condition.

3.2.3. Influence of Rare Earth Y on Impact Properties of GCr15 Bearing Steel under Different Heat Treatments

To investigate the effect of rare earth Y on the impact properties of GCr15 bearing steel under different heat treatments, it was evaluated by the magnitude of impact energy absorbed and fracture morphology. Under hot rolled conditions, the longitudinal impact absorbed energy was increased from 3.20 J to 3.70 J and the transverse impact absorbed energy was increased from 2.50 J to 2.73 J. In the annealed condition, the impact absorption energy of the longitudinal impact increased from 23.70 J to 24.30 J. The absorption energy of the transverse impact increased from 21.47 J to 22.60 J. The absorption energy of the longitudinal impact increased from 7.17 J to 8.67 J in the quenched and tempered condition. The transverse impact absorption energy increased from 6.25 J to 6.75 J. The results are shown in Figure 14. After the addition of rare earth Y, the impact properties of GCr15 bearing steel under the hot rolled, annealed and quenched and tempered conditions were improved.

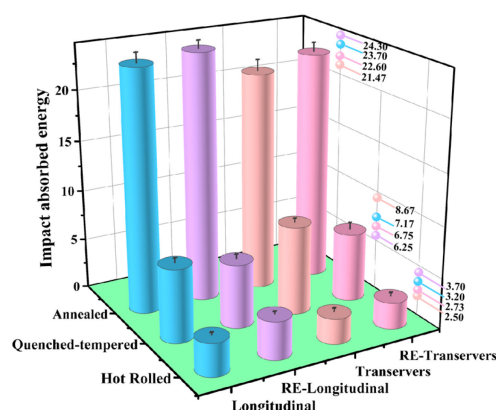


Figure 14. Transverse and longitudinal impact absorption energy of GCr15 and RE-GCr15 bearing steels in hot rolled, annealed and quenched and tempered condition.

In the hot rolled condition, the GCr15 crack in Figure 15a extended from the fracture source in all directions. The enlarged view of the fracture source in Figure 15(a₁,a₂) shows that the fracture surface is relatively flat and smooth with cleavage features. However, the fracture source of RE-GCr15 was rougher, as shown in Figure 15(b₁). This means that RE-GCr15 absorbed more energy during the fracture process. By adding the rare earth element Y to the steel, rare earth oxysulphides were formed with S and O in the steel, as shown in Figure 15(b₂). The formation of RE oxysulphides can eliminate local weaknesses caused by S and P atoms at grain boundaries, thereby improving grain boundary strength and impact resistance [55–58].

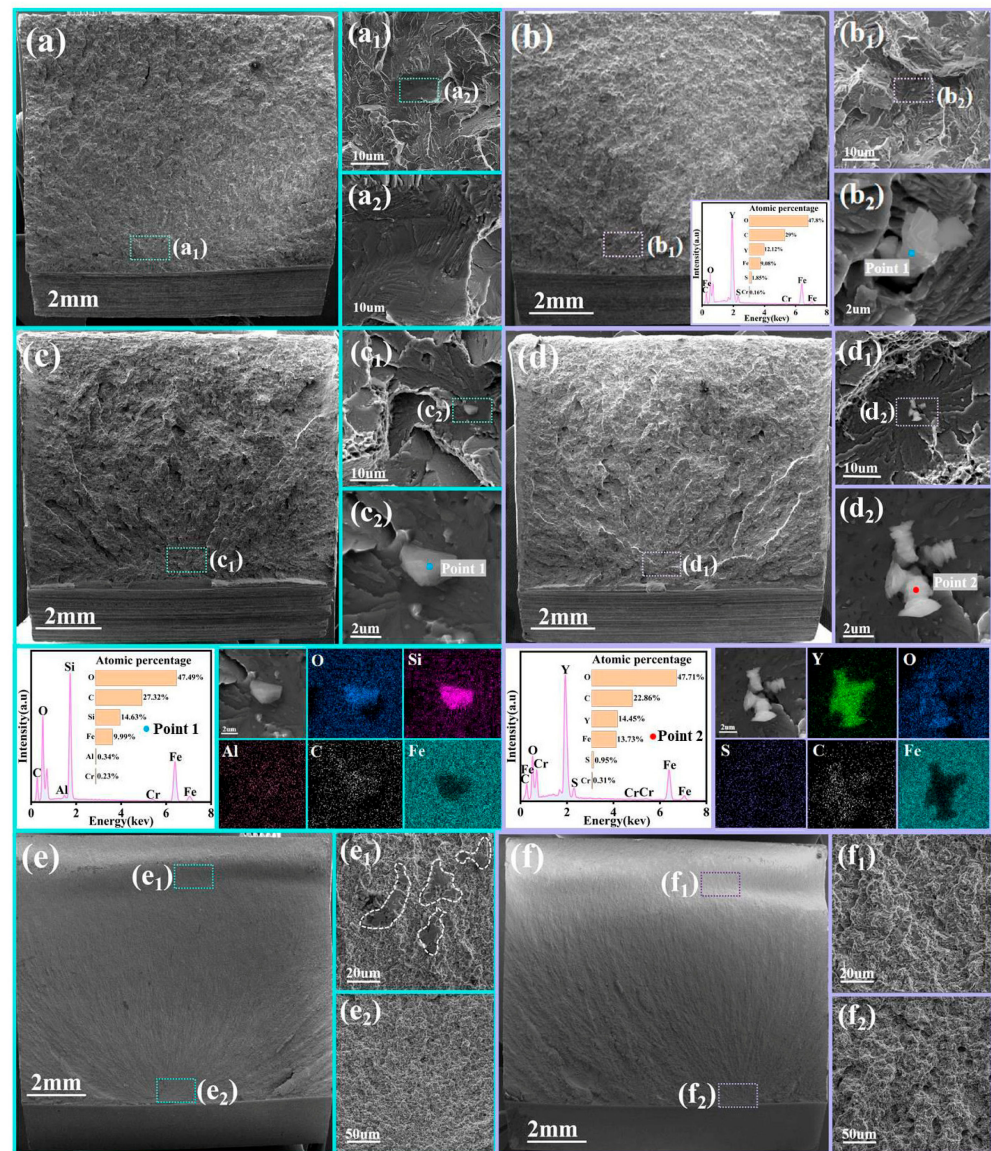


Figure 15. Impact fracture surface morphology and energy spectrum diagrams for GCr15 (a,c,e) and RE-GCr15 (b,d,f) in hot rolled (a,b), annealed (c,d) and (e,f) quenched and tempered conditions; (a₁,b₁,c₁,d₁,e₁,f₁) are enlarged plots of the marked positions in the graph (a,b,c,e,f) and (a₂,b₂,c₂,d₂,e₂,f₂) are enlarged plots of the marked positions in the graph (a₁,b₁,c₁,d₁,e₁,f₁), respectively.

In the annealed condition, Figure 15c shows the fracture source of the GCr15 bearing steel. There are some dimples on the fracture edge near the fracture source, as shown in (c₁), which are caused by oxide-type inclusions as shown in Figure 15(c₂, point1). After RE Y is added to the steel, the area around the fracture source, shown in Figure 15(d,d₁), becomes

rougher, the fracture edges become thicker, the oxide-type inclusions are transformed into RE oxysulphides, more ductile dimples appear and inclusions are uniformly fragmented, as shown in Figure 15(d₂, point 2). This indicates that the RE inclusions and thick fracture edges absorbed more energy during the fracture process and therefore have a higher impact absorption capacity. The improvement in impact toughness can be attributed to the refinement of inclusions by rare earth elements during the solidification process [30,59]. Larger inclusions reduce energy consumption by promoting intergranular fracture and causing rapid crack propagation [27]. Studies have shown that the modification of inclusions and elimination of defects by rare earth elements can also improve the properties of steel [59].

The fracture surface and the fracture source of quenched and tempered GCr15 are relatively flat Figure 15(e,e₂), while the fracture surface and the fracture source of RE-GCr15 are rougher Figure 15(f,f₂). Furthermore, the region in Figure 15(e₁) has a larger cleavage area, whereas the region in Figure 15(f₁) with rare earth does not show any cleavage. This may be due to the fact that rare earth improves toughness and reduces temper embrittlement through grain boundary segregation [60,61]. Theoretical calculations also suggest that the grain boundary segregation of rare earth can improve the toughness of iron-based materials by strengthening the grain boundaries [62,63].

In summary, the impact toughness of GCr15 bearing steel was improved under different heat treatment processes after the addition of rare earth Y to GCr15 bearing steel.

3.3. Effect of Rare Earth Y on Fatigue Properties of GCr15 Bearing Steel

3.3.1. Effect of Rare Earth Y on Fatigue Strength of GCr15 Bearing Steel

In order to improve the service life of bearings, bearing steel must have a high fatigue strength. Therefore, the influence of rare earth on the fatigue properties of GCr15 bearing steel was studied through an axial load fatigue test. Figure 16 shows the S-N data points of the fatigue specimens of GCr15 bearing steel and RE-GCr15 bearing steel. The arrow indicates the specimen that did not fail at the fatigue life limit of 10^7 cycles. After fitting [64], RE-GCr15 has a flatter fit line and has a higher number of cycles for the same stress amplitude difference (25 MPa). When the stress ratio $R = -1$ and the fatigue life of both is 10^7 cycles, the fatigue strength of GCr15 is 1150 MPa while that of RE-GCr15 is 1175 MPa, and RE-GCr15 has a higher fatigue strength.

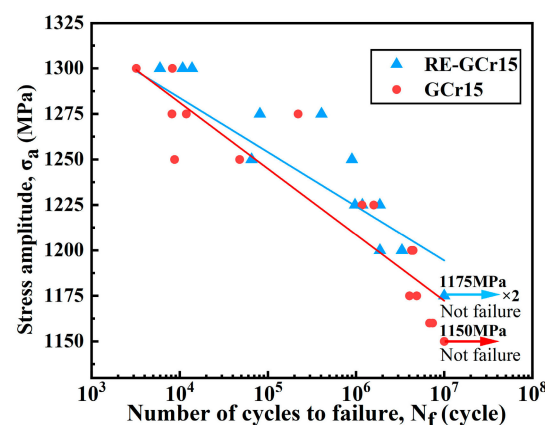


Figure 16. S-N curves of GCr15 and RE-GCr15.

The results show that RE-GCr15 has a higher fatigue strength under the same fatigue life (10^7 cyc), which increases the fatigue strength by about 2.2%, as shown in Figure 16.

3.3.2. Effect of Rare Earth Y on Fatigue Cracking Mode

Further investigation shows that fatigue cracking occurs mainly from two modes: surface cracking and internal cracking caused by inclusions. As the depth and position of the inclusions change, the fatigue life increases as shown in Figure 17a,b. Both groups of specimens follow this rule.

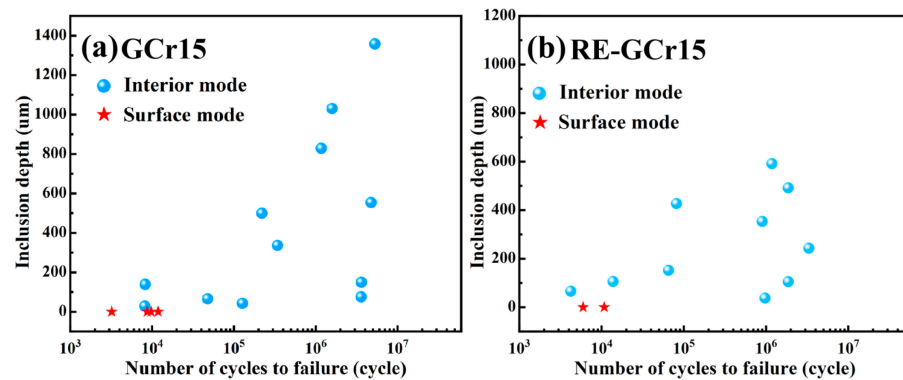


Figure 17. Size distribution of inclusion depths of surface cracks and internal cracks of (a) GCr15 bearing steel and (b) RE-GCr15 bearing steel.

3.3.3. Effect of Inclusion Types on GCr15 Bearing Steel and RE-GCr15 Bearing Steel

Further observation shows that the inclusions causing fatigue fracture in GCr15 bearing steel are Al_2O_3 , $\text{Al}_2\text{O}_3\text{-MnS-Ti (N,C)}$, MnS-Ti (N,C) , $\text{MgO-Al}_2\text{O}_3$ and CaO . The influence of the frequency and type of inclusion-induced fracture during fatigue fracture is discussed. The highest number of fractures was caused by the surface and Al_2O_3 , followed by MnS-Ti (N,C) and $\text{Al}_2\text{O}_3\text{-MnS-Ti (N,C)}$, and the lowest number of fractures was caused by $\text{MgO-Al}_2\text{O}_3$ and CaO . These were ranked according to the degree of hazard: $\text{Al}_2\text{O}_3 < \text{MnS-Ti (N,C)} < \text{Al}_2\text{O}_3\text{-MnS-Ti (N,C)} < \text{MgO-Al}_2\text{O}_3 < \text{CaO}$, as shown in Figure 18a. From the comparative study it can be seen that the composite inclusions tend to have a lower fatigue life. In terms of the likelihood of cracking, probably due to the differences in expansion coefficients and hardness between the different types of inclusions, there will be a greater likelihood of cracking between the composite inclusions and the matrix and between the different phases of the inclusions under cyclic loading. Therefore, the more compound the types of inclusions, the greater the possibility of causing fatigue fracture. After the addition of rare earth Y, $\text{Y}_2\text{O}_2\text{S-Ti (N,C)}$ and $\text{Y}_2\text{O}_2\text{S}$ caused the highest frequency of cracking, followed by surface-induced fracture, and YS caused the lowest frequency of fracture. The degree of hazard was ranked as $\text{YS} < \text{Y}_2\text{O}_2\text{S-Ti (N,C)} < \text{Y}_2\text{O}_2\text{S} < \text{surface cracking}$, as shown in Figure 18a,b. Figure 18c,d shows the distribution of the microstructure eigenvalues of GCr15 and RE-GCr15 in the confidence interval. The addition of rare earth Y modifies the sulphide type composite inclusions into YS, $\text{Y}_2\text{O}_2\text{S-Ti (N,C)}$ and $\text{Y}_2\text{O}_2\text{S}$ and exhibits a higher fatigue life. It is worth noting that the addition of rare earth Y can, on the one hand, reduce the type of composite phase and reduce the chance of crack-induced cracking. On the other hand, it can improve the effect of multi-phase composite type inclusions on fatigue life because it has a coefficient of thermal expansion close to that of the matrix, which will reduce the effect of stress concentration on the matrix and thus improve fatigue life. In addition, the addition of rare earth Y reduces the size of the inclusions and makes them finer and more diffuse, which also contributes to fatigue life improvement.

Under the same cyclic load of 1275 MPa, the inclusion at the fatigue crack source of GCr15 bearing steel was CaO . As shown in Figure 19a,b, cracks appeared in CaO , indicating that the internal binding force of the CaO inclusion was weak and the cyclic fatigue life was low, 8.15×10^3 cycles. However, the fatigue life of cracks caused by Al_2O_3 was high, 2.19×10^5 cycles, as shown in Figure 19c,d. In addition, the morphology of both was close to spherical, indicating that the fatigue property of bearing steel is more sensitive to the size and type of inclusions. The sensitivity to the number of inclusions was much smaller than the influence of the size and type of inclusions.

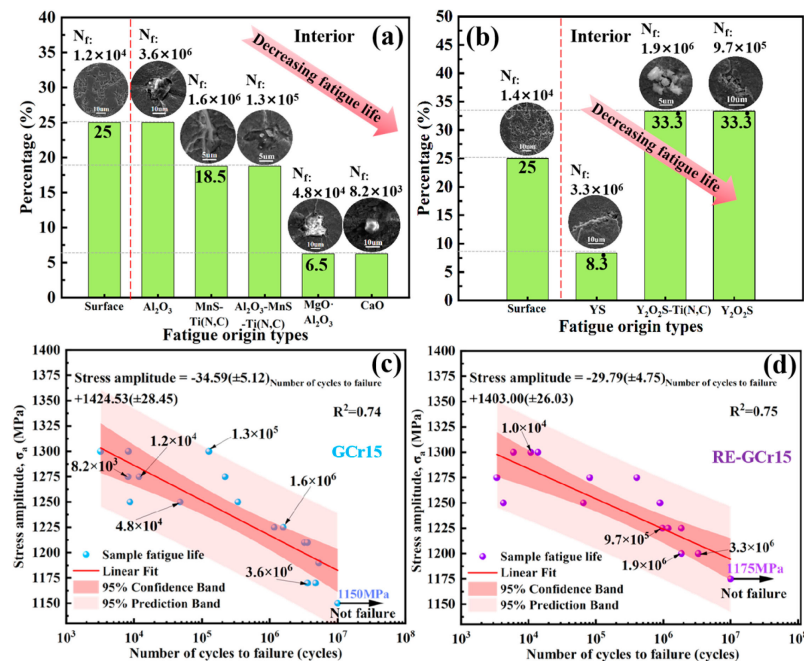


Figure 18. The relationship between the fracture frequency of (a) GCr15 bearing steel and (b) RE-GCr15 bearing steel and the type of inclusions. The distribution of the microstructure characteristic values of (c) GCr15 and (d) RE-GCr15 in the confidence interval.

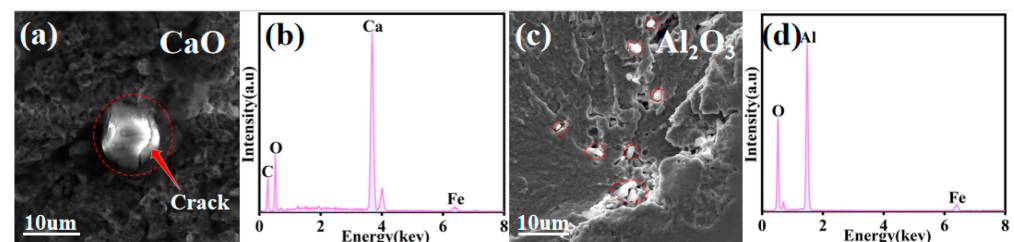


Figure 19. Fracture morphology of two inclusions in GCr15 bearing steel under 1275 MPa load.

After rare earth Y is added, rare earth Y can modify oxides and manganese sulphide to form rare earth Y_2O_3 -Ti (N,C), Y_2O_3 S-Ti (N,C) and YS. As shown in Figure 20a–d, under the same cyclic stress of 1250 MPa, the fatigue life of MgO - Al_2O_3 was 4.8×10^4 and the fatigue life of MnS-TiC was 3.4×10^5 . The addition of rare earth Y causes primary oxide (MgO - Al_2O_3) to form fine rare earth oxide Y_2O_3 -Ti (N,C) and MnS-Ti (N,C) to transform into Y_2O_3 S-Ti (N,C), and the fatigue life of Y_2O_3 -Ti (N,C) formed by rare earth modified inclusion was 1.9×10^6 . The fatigue life of fracture induced by Y_2O_3 S-Ti (N,C) was 8.9×10^5 , and the fatigue life was increased by about 3770% and 163%, respectively. As the coefficient of thermal expansion of the RE inclusions was similar to that of the matrix, stress concentration in the casting process was reduced and fatigue strength was increased [27,65]. The modified RE inclusions were finer and more dispersed, which also improved the fatigue performance of the bearing steel [66]. On the one hand, the segregation of RE at grain boundaries can improve grain boundary cohesion. On the other hand, after the addition of rare earth Y, the grain of GCr15 bearing steel can be refined and the fatigue performance of the bearing steel can be improved. In addition, Ti (N,C) was always formed around Al_2O_3 and MnS, and the existence form of Ti did not change significantly with the addition of rare earth Y.

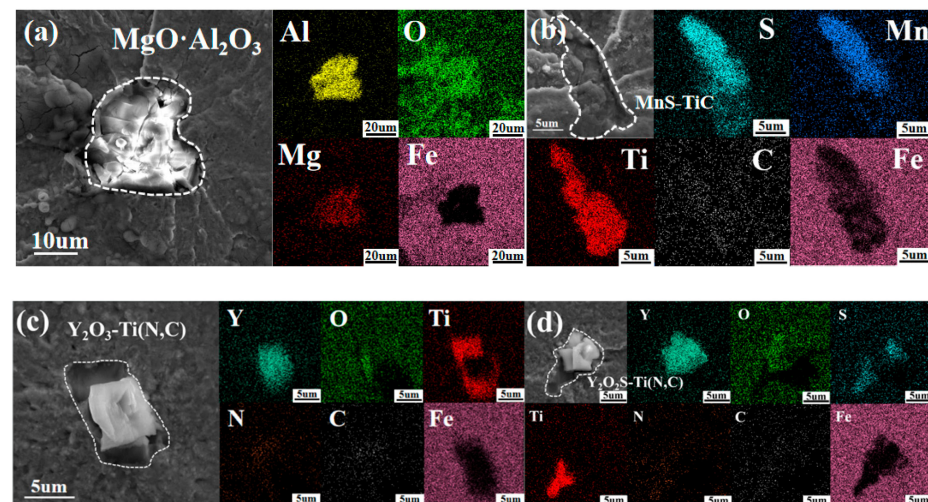


Figure 20. Inclusions in GCr15 bearing steel: (a) $\text{MgO} \cdot \text{Al}_2\text{O}_3$; (b) MnS-Ti (N,C) and RE-GCr15 bearing steel; (c) $\text{Y}_2\text{O}_3\text{-Ti (N,C)}$ and (d) $\text{Y}_2\text{O}_2\text{S-Ti (N,C)}$.

Compared with previous research work, Zhao et al. [37] added mixed rare earth La and Ce to GCr15 bearing steel, and the hardness after quenching and tempering increased from 537.6 HV to 560.3 HV, an increase of 4.22%, the tensile strength increased from 1229 MPa to 1279 MPa and the average grain size decreased from 2.75 μm to 2.33 μm . Under 107 cycles, the fatigue strength of GCr15 bearing steel was increased from 758 MPa to 768 MPa. In this study, after the addition of rare earth Y, the hardness of quenched and tempered GCr15 bearing steel was increased from 560.2 HV to 636.3 HV, an increase of 13.58%, the tensile strength was increased from 2134 MPa to 2217 MPa and the average grain size was reduced from 0.65 μm to 0.43 μm . The fatigue strength of GCr15 bearing steel was increased from 1150 MPa to 1175 MPa, an increase of approximately 2.2%. Compared with the research of Zhao et al., the heat treatment process in this paper can cause GCr15 to have higher hardness, tensile strength, fatigue strength and fatigue life. Meanwhile, the addition of rare earth Y can further improve the mechanical properties of GCr15 bearing steel. Through the heat treatment process and the addition of rare earth Y, the GCr15 bearing steel has higher hardness, higher tensile strength, smaller grain size, higher fatigue limit and improved longitudinal and transverse impact toughness.

4. Conclusions

The effects of rare earth Y on the microstructure, mechanical properties and fatigue properties of GCr15 bearing steel under hot rolled, annealed and quenched and tempered conditions have been investigated. Rare earth Y has little effect on the properties of GCr15 bearing steel under annealed conditions. The main conclusions about the structure and properties of GCr15 bearing steel under hot rolled and quenched and tempered conditions are as follows:

Rare earth Y improves grain boundary carbide formation in hot rolled steel, reduces pearlite lamellar spacing and improves hardness, tensile and impact properties of steel, which are related to changes in grain boundary segregated rare earths, grain refinement and fracture morphology (the type of inclusion at the fracture source, the size of the cleavage area and the roughness).

The rare earth element Y improves the hardness, tensile and impact properties in the quenched and tempered condition. The reason for the increase in hardness is due to the increase in carbon content in the martensite. The tensile and impact fractures in the quenched and tempered state showed almost no inclusions. In this state, the type of inclusion has little effect on the tensile and impact properties. The improvement in tensile and impact properties is mainly related to grain refinement and carbide (size reduction, shape tending to spherical, uniform distribution and phase volume fraction increase).

The rare earth Y element improves the fatigue performance in the quenched and tempered state. Rare earth Y elements can improve the fatigue strength of materials, and at the same time, rare earth Y elements tend to refine and modify inclusions, which improves the reliability and stability of fatigue properties.

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