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Effect of Sulfur Content on the Composition of Inclusions and MnS Precipitation Behavior in Bearing Steel

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Abstract: MnS inclusions in bearing steel have long been considered to significantly affect the fatigue life of bearing steel. In this paper, the sizes of inclusions in bearing steel with different sulfur contents were analyzed and the precipitation behavior of MnS was calculated using thermodynamics. Furthermore, the positive role of MnS in bearing steel was discussed. Results showed that when the size of inclusions in bearing steel was increased, the proportion of MnS components in composite inclusions gradually decreased. When the sulfur content was increased, the shape of inclusions changed from a particle shape to a strip shape. With increasing MnS content, the inclusion ratio of Al_2O_3 was significantly reduced in the Al_2O_3 –CaO–MgO–MnS quaternary inclusion system, particularly for MnS proportions greater than 20%. The content of sulfur in bearing steel significantly affects the precipitation temperature of MnS. When sulfur content increases from 0.001% to 0.007%, the precipitation temperature of MnS increases from 1493 K to 1633 K as the precipitation of MnS moves from the austenite solid phase to the liquid and solid phases, and the precipitation size of MnS inclusions significantly increases. The size of oxide inclusions should be controlled to improve MnS wrap oxide inclusions in steel. Based on these results, a composition control with high sulfur levels and low oxygen levels should be adopted to improve the fatigue performance of steel.

Keywords: bearing steel; MnS; composite inclusion; thermodynamics; fatigue property

1. Introduction

Sulfur is generally considered to be one of the most harmful elements remaining in steel, easily causing the hot embrittlement of steel and reducing its mechanical properties. A common solution to this problem is to increase $w(\text{Mn})/w(\text{S})$ to improve the high-temperature ductility of steel, where sulfur can be used in MnS to improve steel and reduce the formation of low melting compounds such as FeS in the austenite grain boundary [1,2].

MnS causes problems in various types of steel. With an increase in sulfur content, the transverse elongation of the carbon steel plate was significantly reduced [3]. During heat treatment at 1523 K, MnS hindered the grain growth of the recrystallization annealing, leading to the deterioration of core loss [4]. The resistance to hydrogen-induced cracking (HIC) of pipeline steel in a wet H_2S environment is related to the shape and the distribution of MnS. When the amount of MnS in steel exceeded a certain quantity, the resistance to HIC was significantly reduced [5]. MnS also was a preferential corrosion phase in the structure of weathering steel. Adding sulfides formed by rare earth elements could significantly improve resistance to industrial atmospheric corrosion [6]. Besides these issues, it may also have a beneficial effect on the properties of steel. In free cutting steel, a uniform and fine MnS content could improve cutting performance [7]. Sulfur acts as a highly surface-active element

that reduces surface tension and the viscosity of steel melts. Sulfides are beneficial in the laser cutting of steel [8].

The most important aspect of bearing steel is its fatigue resistance, and its inclusion size and composition are the most important factors that affect this [9]. The reactions between the oxide inclusions in bearing steel during smelting [10,11], the influence of the inclusion sizes on bearing steel fatigue and other properties [12–14] as well as the use of rare earth elements in bearing steel to modify inclusions [15,16] have all been widely studied. Research on MnS in bearing steel has primarily centered on oxide–sulfide complex inclusions formation mechanism [17–19] and the interaction between MnS and oxides [20].

At present, there are few reports on the positive role of MnS in bearing steel. Drar [21] studied an alloy steel and found that MnS did not contribute to fatigue crack initiation or the crack propagation mechanism. Scurria [22] found that the ratio of the length and thickness of MnS to a certain value significantly affected the fatigue performance of bearing steel.

This paper analyzes the inclusions in bearing steels with different sulfur contents and calculates the precipitation of MnS in bearing steel by using thermodynamic methods. It discusses the positive role of MnS in bearing steel, which improves its resistance fatigue performance.

2. Materials and Methods

Two high-carbon bearing steels produced by an enterprise, grades SUJ2 and GCr15, were selected for testing. Their chemical compositions are shown in Table 1. The process route of the bearing steel was as follows: a 100 t ultra-high power arc furnace was used for the molten steel smelting, and the steel was produced using an eccentric bottom method. High alkalinity refining treatment and aluminum deoxidation were used in the 100 t refining furnace and vacuum degassing for no less than 20 min was performed in the 100 t vacuum degassing furnace. A five-machine five-stream continuous casting machine was used for the casting billet production, and a 17-bar continuous rolling mill was used for the hot rolling production.

Table 1. Chemical composition of bearing steel samples.

Elements	C	Si	Mn	P	S	Cr	Mo	Ti	Al	O
1#	0.99	0.25	0.41	0.01	0.007	1.35	0.019	0.001	0.015	0.0002
2#	0.96	0.27	0.39	0.009	0.001	1.57	0.01	0.002	0.014	0.0006

Samples of 10 mm × 10 mm × 10 mm in size were cut from the bearing steel rolled products. After rough grinding, fine grinding and polishing, they were made into metallographic samples. The samples were cut along the rolling direction of the bearing bar and the sampling position of the cross section was at a 1/2 radius. Then, the number, size and composition of the inclusions in the different bearing steel samples were analyzed using an ASPEX SSX-550 automatic scanning electron microscope (ASPEX Inc., Pittsburgh, PA, USA).

The solidification process of Al₂O₃–CaO–MgO–MnS inclusions with different MnS contents was calculated by using Factsage 7.3 thermodynamics software (Thermfact/CRCT, Montreal, QC, Canada and GTT-Technologies, Aachen, Germany), which was authorized by the Central Iron and Steel Research Institute. The calculation process mainly involved two databases, FToxid and FSstel. The precipitation behavior of MnS in the bearing steel was analyzed using the metallurgical thermodynamic method.

A three-point contact fatigue test was performed using a ball-rod contact fatigue test machine (Nantong University, Jiangsu, China), which used 20 pieces of two bearing steel products with a diameter of 10 mm. The loading times to the contact of the steel bar of the test machine were 2.49×10^5 per hour, at a loading strength of 3900 N and a speed of 1800 r/min. The fatigue test results determined the fatigue life performance of the two bearing steels.

The examination of the inclusion in bearing steel was conducted using ASPEX automatic scanning electron microscopes manufactured by the ASPEX company in the United States, which perform the

basic function of conventional scanning electron microscopes as well as the calculation of automatic statistics for the inclusion information from the sample cross-section. The working principle of the ASPEX SEM is shown in Figure 1. The accelerating voltage adjustment range of the equipment was 0.2–25 kV and the amplification was 20–250,000 times. The inclusion size range of the device was 0.07 μm –8 mm. Because of the detection efficiency and critical size of inclusions in bearing steel fatigue failure, the minimum size of the inclusions detected in this experiment was 1 μm . The equipment accurately determined the maximum diameter, minimum diameter and the surface area of the inclusions using eight strings passing through the center of the inclusions [23].

Figure 1. Working principle of ASPEX: (a) search and measure grid; (b) typical characteristic image.

3. Results and Discussion

3.1. Morphology of Inclusions in Bearing Steel with Different Sulfur Contents

The morphology and size characteristics of the inclusions in bearing steels 1 and 2 are shown in Figures 2 and 3. In these figures, Dmax indicates the maximum diameter of inclusion (μm), Dmin indicates the minimum diameter of inclusion (μm) and area indicates the surface area of inclusion (μm^2). Compared with the traditional inspection method, ASPEX can more directly calculate the area of inclusions and more accurately analyze the size and morphology characteristics of inclusions in the steel. The inclusions in steel 1 are mostly strip-shape, whereas the inclusions in steel 2 are rounder and more elliptical.

Figure 2. Shape and size of the inclusions in bearing steel 1: (a) round; (b) strip and round; (c) polygonal; (d) Strip; (e) strip; (f) strip and round; (g) strip; (h) strip.

Figure 3. Shape and size of the inclusions in bearing steel 2: (a) round; (b) round; (c) round and ellipse; (d) rhombic; (e) ellipse; (f) polygonal; (g) round; (h) round.

The energy spectrum inspections of the typical inclusions in bearing steels 1 and 2 are shown in Figures 4 and 5. The steel 1 sample was mainly composed of MnS and Al_2O_3 composite inclusions, with a small amount of MgO, CaO and MnO. The composition of the inclusions in the steel 2 sample mainly included composite inclusions of granular calcium aluminate and MnS, with the composition being largely Al_2O_3 , MgO, CaO and MnS.

Figure 4. EDS analysis of bearing steel 1: (a) Al_2O_3 -MgO-CaO; (b) Al_2O_3 -MgO-CaO-MnS; (c) MnS; (d) Al_2O_3 -MgO.

Figure 5. EDS analysis of bearing steel 2: (a) Al_2O_3 - MgO - MnS ; (b) Al_2O_3 - MgO ; (c) Al_2O_3 - MgO - CaO - $\text{MnS}(\text{CaS})$; (d) Al_2O_3 - MgO - CaO - MnS .

Using ASPEX to scan the $10\text{ mm} \times 10\text{ mm}$ areas on the surfaces of each sample line by line, the inclusions in the bearing steel samples was counted and the content of MnS in each inclusion was analyzed using EDS of ASPEX, as shown in Table 2. To facilitate the calculation of the statistics for MnS in inclusions, the CaS in inclusions was ignored because of the minuscule content of Ca in the inclusions of bearing steel.

Thirty inclusions were found on the cross-section of sample 1, of which inclusions containing MnS accounted for 96% of the total quantity. One hundred twenty-eight inclusions were found on the cross-section of sample 2 and MnS -containing inclusions accounted for 81.3% of this quantity. It can be seen that MnS is an important component of the composite inclusions in bearing steel. Figure 6 shows a statistical analysis of the shape of the inclusions from samples 1 and 2. When the ratio of the maximum diameter to the minimum diameter of the inclusion satisfied $D_{\text{max}}/D_{\text{min}} > 2$, the composite inclusions were considered to be a long-shaped. When $D_{\text{max}}/D_{\text{min}} < 2$, the composite inclusions were considered to be circular or oval. As can be seen in Figure 6, the proportion of strip-shaped inclusions in sample 1 is 86.7% and the proportion of strip-shaped inclusions in sample 2 is 7.1%. This shows that the sulfur content of bearing steel significantly affected the shape of the composite inclusions in the steel.

Some literature has shown that the size of endogenous inclusions ($<50\text{ }\mu\text{m}$) during the refining and deoxidation of bearing steel decreases significantly as the total oxygen content is reduced [24]. However, the current study found that when the sulfur content in bearing steel was significantly increased, the size of the inclusions in the steel did not decrease. These inclusions mainly consisted of

MnS composite inclusions. Therefore, it is very important to understand the effect of MnS on bearing steel composite inclusions.

Table 2. Statistics of the inclusions in the different bearing steel samples per square centimeter.

Inclusion Composition	TiN	MnS	Complex Inclusion with MnS	No MnS Complex Inclusion	Total Number of Inclusions	Percentage of MnS Inclusions
1#	0	7	22	1	30	96.7%
2#	2	0	104	22	128	81.3%

Figure 6. Dmax/Dmin of the inclusions in the bearing steel samples 1 and 2.

3.2. Relationship between Size and Composition of Inclusions in Bearing Steel

It can be concluded from the ASPEx inspection that the majority of the inclusions in bearing steel were composite inclusions containing MnS. The size distribution of the composite inclusions in bearing steel and the relationship between the size and ratio of MnS in the inclusions are shown in Figure 7. The area containing the most inclusions in sample 1 was found at 5–20 μm^2 , with the maximum mass fraction of MnS in the composite inclusions being 37%. The area with the most inclusions in sample 2 was found at 2–10 μm^2 , with the maximum mass fraction of MnS in the composite inclusions at 16%. The proportion of MnS in the composite inclusions in sample 1 was larger than that in those in sample 2. It can be seen that with an increase in the size of the inclusions in bearing steel, the proportion of MnS in the impurities gradually decreases. Both bearing steels showed the same regularity. Therefore, MnS has an obvious wrap effect on the inclusion of small-scale oxides in bearing steel.

Figure 7. Size distribution and MnS ratio of composite inclusions in bearing steel: (a) sample 1; (b) sample 2.

It has been reported [22] that within a certain range of inclusion sizes and Dmax/Dmin ratios of MnS in steel, MnS can wrap oxide inclusions, which could effectively improve the thermoplasticity of

steel without reducing its fatigue life. In the current study, it was found that the effect of coating oxides with MnS was worse when only the sulfur content was increased, but the total oxygen content in steel was not controlled throughout the production process.

To analyze the relationship between the size of the composite inclusions and the various components in bearing steel, the Al_2O_3 –MgO–CaO–MnS quadruple of composite inclusions in bearing steel samples 1 and 2 was analyzed, as shown in Figure 8.

It was found that when the total oxygen content in bearing steel was low, there were fewer CaO and MgO inclusions in the bearing steel sample 1 composite inclusions, leaving mainly MnS and Al_2O_3 composite inclusions. The composition of the inclusions in sample 2 changed from Al_2O_3 –MgO–CaO–MnS to MgAl_2O_4 spinel inclusions when size of composite inclusions was increased. The nucleation of MnS on MgAl_2O_4 spinel inclusions was caused by a lattice disorder mechanism, which reflected the heterogeneous nucleation and growth of MnS on the spinel inclusions [17]. When the sulfur content in bearing steel sample 2 was low, the proportion of MnS in the small inclusions was high, but was low in the large inclusions. Although large-scale oxide inclusions are the main factor in the fatigue failure of bearing steel, MnS has an obvious effect in low sulfur bearing steel on the inclusion of small-scale oxides, which is not conducive to the positive role of sulfur.

Figure 8. Ternary phase diagram of the composite inclusion components Al_2O_3 , MgO, CaO, MnS in bearing steel: (a) sample 1; (b) sample 2.

3.3. Thermodynamic Calculation of Al_2O_3 –CaO–MgO–MnS with Different MnS Contents

The liquid phase projection diagram of the Al_2O_3 –CaO–MgO–MnS system was calculated using the Factsage thermodynamics software (Thermfact/CRCT, Montreal, QC, Canada and GTT-Technologies, Ahern, Germany), and the influence of 5%, 10%, 20% and 40% MnS contents on the composition of quaternary inclusions were analyzed, as shown in Figure 9. It can be seen that when the MnS content was increased, the low melting point region where the inclusions were expected to be in the liquid phase decreased gradually and moved away from the Al_2O_3 composition.

The most critical factors affecting the fatigue life of bearing steel are the hard inclusions with the largest particle sizes such as Al_2O_3 and TiN [25]. When the MnS content increases, the proportion of Al_2O_3 in Al_2O_3 –CaO–MgO decreases, and the proportion of CaO increases. When the Al content in bearing steel is held constant, increasing the S content can cause the Al_2O_3 in the inclusion to become finer and more dispersed, especially when the MnS proportions reach more than 20%.

The effect of MnS on the composition of the inclusions in steel is mainly achieved by affecting the levels of Ca and Mg. The order in which the elements in steel combine with S to form sulfides is Ca, Mg, Ti, Mn and then Fe. When the S content in steel increases, it promotes the formation of CaS and MgS, which causes the reduction of CaO and MgO. It had been reported that when the proportion of CaO decreased, the area of the low-temperature liquid phase region decreased in the quaternary inclusion system of MnO–CaO– SiO_2 – Al_2O_3 [26].

Therefore, the proper increase of sulfur content in bearing steel, which increases the proportion of MnS in inclusions, can reduce the proportion of Al_2O_3 in the composite inclusions. This is very beneficial to improve the fatigue strength of bearing steel.

Figure 9. Liquid phase projection of the Al_2O_3 –CaO–MgO–MnS system with different MnS contents: (a) 5% MnS; (b) 10% MnS; (c) 20% MnS; (d) 40% MnS.

3.4. Thermodynamic Analysis of MnS Precipitation Behavior of Bearing Steel

In this section, the precipitation behavior of MnS and the mass fraction change of MnS precipitation during the solidification of two experimental steels were calculated using metallurgical thermodynamics. The calculation of the mass fraction of precipitated MnS does not consider any kinetics of the precipitation or the growth rate of MnS inclusions.

The reaction Equations (1) [27] for the formation of MnS in the molten steel and the reaction equilibrium constant (2) for MnS were obtained, and the equilibrium reaction Equation (3) was found to be as follows:

$$K_{\text{MnS}} = \frac{a_{\text{MnS}}}{a_{[\text{Mn}]}a_{[\text{S}]}} = \frac{1}{f_{\text{Mn}}w_{[\text{Mn}]}f_{\text{S}}w_{[\text{S}]}} \quad (2)$$

$$\log K_{\text{MnS}} = \frac{-\Delta G^\ominus}{2.3RT} = \frac{8827.9}{T} - 5.17 \quad (3)$$

where K_{MnS} represents the reaction equilibrium constant of MnS, T represents the reaction temperature (K), R represents the ideal gas constant 8.314 J/(mol·K), and f_{MnS} and f_S are the activity coefficients of Mn and S in molten steel, respectively.

According to Wagner's first-order interaction coefficient, Raoult's law and Henry's Law, the activity coefficient f_i of the solidification front is as follows:

$$\log f_{i(1873K)} = \sum (e_{i(1873K)}^j w[j]) \quad (4)$$

The influence of the different elements in molten steel on the activity coefficients of Mn and S is shown in Table 3.

Table 3. Interaction coefficients of Mn and S in molten steel at 1873 K [28].

e_i^j	C	Si	Mn	P	S	Cr	Mo	Al	O	Ti
Mn	−0.07	0	0	−0.0035	−0.048	0	0	0	−0.083	0
S	0.11	0.063	−0.0026	0.029	−0.028	−0.011	0.0027	0.035	−0.27	−0.072

The solid solubility products of bearing steel sample 1 and 2 in the MnS equilibrium state were calculated to be as follows:

$$\log(w[S]w[Mn]) = -\frac{8827.9}{T} + 5.13 \quad (5)$$

Moreover, considering the solid-state rate during solidification, temperature changes at the solidification front are as follows:

$$T = T_0 - \frac{T_0 - T_L}{1 - f_{s0}(T_L - T_S)/(T_0 - T_S)} \quad (6)$$

T_0 represents the melting point of pure iron, whereas T_L represents the liquidus temperature of steel, T_S represents the solidus temperature of steel, f_{s0} represents the solid phase ratio and T represents the liquidus zone temperature at the solidification front. T_L and T_S were calculated using the Factsage software. The calculated result of T_L in sample 1 was approximately 1724 K and T_S was approximately 1610 K. The values of T_L and T_S in sample 2 were 1727 and 1622 K, respectively. Formulas (5) and (6) can be used to calculate the activity product of Mn and S in the equilibrium during the solidification process of molten steel.

Solute segregation should be considered when calculating the actual activity product of Mn and S during solidification. The components after segregation can be solved for using the Scheil equation of solute redistribution as follows:

$$w[Mn]' = w[Mn] \cdot (1 - f_{s0})^{K_{Mn}-1} \quad (7)$$

$$w[S]' = w[S] \cdot (1 - f_{s0})^{K_S-1} \quad (8)$$

where $w[Mn]$ represents the mass fraction of Mn; $w[S]$ represents the mass fraction of S, f_{s0} presents the solid phase ratio, and K_{Mn} and K_S are the equilibrium partition coefficients of Mn and S in bearing steel, the values of which are shown in Table 4.

Table 4. Diffusion coefficient and equilibrium partition of Mn and S [29].

Element	$D_s'(\text{cm}^2/\text{s})$	K
Mn	$0.055\text{Exp}(-249366/\text{RT})$	0.785
S	$2.4\text{Exp}(-223426/\text{RT})$	0.035

The curve of the MnS solubility product in an equilibrium state and the actual solubility product under the segregation of bearing steel are shown in Figure 10. The curves of the solid phase ratio

with temperature during the solidification of bearing steel samples 1 and 2 are shown in Figure 11, and the mass fraction of MnS precipitated out during the cooling is shown in Figure 12. During the solidification process of bearing molten steel, the actual solubility product of MnS increased and the equilibrium solubility product decreased. When the actual solubility product of MnS was greater than the solubility product in the equilibrium, MnS could be precipitated from the steel.

Figure 10. Solubility product of MnS in the equilibrium and the real state with solid fraction.

Figure 11. Solid fraction changing with temperature during the solidification.

Figure 12. Mass fraction of MnS changing with temperature during the solidification.

The sulfur content in bearing steel significantly affected the precipitation temperature of MnS. The MnS of steel sample 1 began to precipitate at a temperature of 1633 K when the solid phase ratio of

molten steel was 0.96. After solidification, the amount of MnS precipitated was close to 50%, with the rest precipitating in the solid phase. During the solidification process of steel sample 2, MnS did not reach the thermodynamic conditions for precipitation. Precipitation did not occur but did begin in the austenite phase at 1493 K. It is for this reason that the amount of MnS in sample 2 was significantly smaller than that of sample 1, which was consistent with the previous results.

3.5. Fatigue Properties of Bearing Steel with Different Sulfur Contents

A contact fatigue test was carried using a ball bar tester for the two types of bearing steel with different compositions. The test results are shown in Table 5. The P–N curve of the rolling contact fatigue test can be used to judge the fatigue performance of the two types of bearing steels.

Table 5. Contact cycle times of the bearing steel fracture (cycles).

Sample	1	2	3	4	5	6	7	8	9	10
1#	3.45×10^6	2.94×10^6	2.65×10^6	2.68×10^6	0.83×10^6	1.07×10^6	1.34×10^6	0.57×10^6	1.52×10^6	0.42×10^6
2#	1.63×10^6	1.12×10^6	0.98×10^6	1.24×10^6	1.09×10^6	1.83×10^6	0.69×10^6	0.48×10^6	0.75×10^6	1.29×10^6

The rolling contact fatigue life obeys the two-parameter Weibull function [30], with the following expression:

$$P(N)_S = 1 - e^{-\left(\frac{N}{V_s}\right)^b} \quad (9)$$

where $P(N)_S$ is the probability that the sample life is less than N at a certain stress level (%), b represents the slope of the Weibull distribution, N represents the number of stress cycles (fatigue life), V_s is the characteristic life of the Weibull distribution, i.e., the fatigue life when failure probability is 63.2%.

The characteristic value of bearing steel fatigue life and the slope of the Weibull curve are shown in Table 6.

Table 6. Characteristic value of the fatigue life and the Weibull slope of bearing steel by different standards [31].

Sample	L_{10}	k
SUJ2	0.685×10^6	2.214
GCr15	0.543×10^6	3.269

Finally, the P–N curves of the rolling contact fatigue lives of bearing steel are shown in Figure 13. It can be seen that the rolling contact fatigue life of sample 1 is longer than that of sample 2.

Figure 13. P–N curves of the rolling contact fatigue experiments on steel samples 1 and 2.

Composite inclusions in bearing steel composed of oxide and sulfide control the fatigue performance of high cleanliness bearing steel. The fatigue performance of bearing steel with a low sulfur content (0.001% S) is independent of MnS inclusions, whereas the fatigue performance of bearing steel with a high sulfur content (0.006% S) will show anisotropy, which leads to transverse fatigue failure in the specimen [32,33]. The fatigue life of bearing steel depends mainly on the chemical composition of oxide in it. After the fatigue test, it was found that there were cavities around Al_2O_3 and $\text{Al}_2\text{O}_3\cdot\text{CaO}$ inclusions, but no cavities were near MnS inclusions and various composite inclusions [9].

Therefore, it is reasonable to assume that a composition of high sulfur and low oxygen can improve the fatigue property of bearing steel. In this study, it was found that the proportion of MnS in inclusions in bearing steel decreased when inclusion size increased, and that MnS had an obvious wrap effect on small-scale oxide inclusions. When considering an increase in sulfur content in steel to improve the fatigue property, the total oxygen content in the steel must be controlled in a lower range. Additionally, increasing the sulfur content can significantly increase the precipitation temperature of MnS in bearing steel, increasing the stability of MnS inclusions and reducing the defects caused by the precipitation and dissolution of MnS during high-temperature heating. This improves the processing performance of bearing steel.

4. Conclusions

Most composite inclusions in bearing steel contain an MnS component. The proportion of MnS in composite inclusions gradually decreases when the size of the inclusion area is increased. The inclusion shape changes from a particle shape to a strip shape when the content of sulfur in steel is increased.

The projection diagram of the liquid phase of the $\text{Al}_2\text{O}_3\text{--CaO--MgO--MnS}$ system was calculated by Factsage. With an increase in MnS content, the ratio of Al_2O_3 in the $\text{Al}_2\text{O}_3\text{--CaO--MgO--MnS}$ quaternary inclusion system reduced significantly, especially when the MnS proportion reached more than 20%. Therefore, a proper increase in the sulfur content of bearing steel can make Al_2O_3 inclusions in steel finer and more dispersed.

The sulfur content of bearing steel has a significant effect on the precipitation temperature of MnS. When the sulfur content increases from 0.001% to 0.007%, the precipitation temperature of MnS increases from 1493 to 1633 K, the precipitation of MnS changes from an austenite solid to a combination of liquid and solid and the precipitation size of the MnS inclusions increases significantly.

Bearing steel can be manipulated using a composition of high sulfur and low oxygen to improve its fatigue performance. MnS has an obvious wrap effect on the inclusion of small-scale oxides in bearing steel. To enhance the positive role of sulfur content in bearing steel, we should strictly control the oxygen content in steel while appropriately increasing the sulfur content.

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