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Study on Oxygen Content, Inclusions and Fatigue Properties of Bearing Steels Produced by Different Processes

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Abstract: The metallurgical properties and fatigue life of bearing steel processed by electric furnace (EAF), ladle refining (LF-VD), continuous casting (CC) and electroslag remelting (ESR) have been investigated. The main results obtained are as follows: (1) Due to low oxygen content and dispersion inclusions in steel, the fatigue life of LF-VD-IC or CC is three times as high as that of EAF steel; (2) The oxygen content in steel produced by CC process is about 9.0×10^{-6}, the carbon segregation (C/C_0) is from 0.92 to 1.10 and the fatigue life of CC steel is equal to that of ladle refining ingot casting steel; (3) Although the amount of inclusion and oxygen in ESR steel is higher than that of LF-VD-IC or CC steel, the fatigue life of ESR steel is higher than that of the latter because of its fine and well dispersed inclusions.

Key words: bearing steel; ladle refining; continuous casting; electroslag remelting; oxygen content; inclusion; fatigue life

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1 Introduction

Rolling bearings are perhaps the most widespread type of mechanical engineering components for all types of machinery. Bearings of high reliability and long life have been sought with science and technology developing. Bearing steel (containing 1.0%C, 1.5%Cr), invented at the end of the nineteenth century, is one of the most important special steels with its metallurgical quality being the important influencing factors on bearing life.

It is well-known that bearing life can be increased markedly by controlling the amount, type, size, morphology and distribution of oxide inclusions in steel [1–3]. In order to produce low oxygen and low oxide inclusions steel, it is necessary to consider separately the melting process and the refining process. Furthermore, the refractory of the refining vessel and casting system should be considered. The characteristics of inclusions are dependent on the chemical composition of refining slag, deoxidation process, and solidification status.

The mutual efforts of steel producers and bearing manufacturers to ensure a high bearing life, based on material properties and considering economical factors, are established in the specifications for bearing steels. The steels produced by different processes with different properties have different uses. Ladle refining process is suitable for producing common use low oxygen steel. Electroslag remelting in a water-cooled copper mold is a refining process applied to produce special use clean steel by the function of slag. Fine and dispersed inclusion and excellent micro and macrostructure can be obtained by ESR process. But the cost of production for this process is higher.

In this paper, oxygen content, inclusions and fatigue properties of bearing steels produced by electric furnace (EAF), ladle refining (LF-VD), continuous casting (CC) and electroslag remelting (ESR) are studied for the steel advancement.

2 Experimental

The test specimens of GCr15 (SAE52100) bearing steel were cut from hot rolled rounds produced by 18t EAF-IC (EAF), 60 t EAF-LF-VD-IC (IC), 60 t EAF-LF-VD-CC (CC) and ESR processes, respectively. After rolling and spheroidizing annealing at the same condition, the thrust-type fatigue life testing specimens and analysis specimens were prepared. E980 spectrum analysis system and CS344 carbon-sulfur analysis system were used to determine the chemical composition of testing steels. LECORO-316 Oxygen analysis system was used to determine the oxygen content in the steel. Q-970 Image Analysis System was used to determine the inclusion size in steel. Inclusions rating was analyzed according to Chinese YJZ-84 method (the same as ASTM E-45 D method). Thrust-type specimens were quenched in salt bath at 835–845 ℃, and tempered at 150–160 ℃ for 3 h. Rockwell hardness 63 to 64 was obtained on thrust-type life testing specimens.

The test parameters were as follows: specimen, 8206 thrust-type bearing; rotating speed of mainshaft, 2530–3000 r/min; contact stress, 6116–4410 MPa; lubricant, No.20 oil.

3 Test Results

3.1 Oxygen content

The oxygen contents in testing steels for different steelmaking processes are shown in **table 1**. EAF steel oxygen content was the highest with an average oxygen content of 27×10^{-6}. CC steel oxygen content was the lowest with an average oxygen content of 9.3×10^{-6}.

Table 1 Oxygen content of bearing steels

Process	Heats	Oxygen content /$\times10^{-6}$	Average / $\times10^{-6}$
EAF	21	15.0–38.0	27.0
IC	720	4.0–18.0	9.50
CC	9	7.0–13.0	9.30
ESR	103	14.0–31.0	21.23

3.2 Non-metallic inclusion rating

Inclusion ratings determined by Chinese YJZ-84 method (the same as ASTM E-45 D method) are listed in **table 2**. Type A heavy, B heavy, C and D inclusion ratings for all processes are zero, as shown in table 2.

Table 2 Nonmetallic inclusion rating (YJZ-84)

Process	A (thin)		B (thin)		C	D
	Rating	Average	Rating	Average		
EAF	0.5–4.0	1.33	0.5–4.0	1.12	0	0
IC	0.5–3.5	1.30	0.5–3.5	1.06	0	0
CC	0.5–2.0	1.15	0.5–1.5	1.03	0	0
ESR	0.5–2.0	1.12	0.5–2.0	1.08	0	0

3.3 Inclusion size

The size of type B inclusions in steel for different steelmaking processes is listed in **table 3**.

Table 3 Inclusion size of type B determined by quantimet

Size	EAF	IC	CC	ESR
Average / μm^2	8.9	6.7	6.5	3.8
Maximum / μm^2	75	60	60	15
Minimum / μm^2	0.5	0.5	0.5	0.5
Oxygen content / $\times10^{-6}$	28.6	8.2	9.3	18.6

3.4 Carbon content distribution in CC bearing steel billet

Effects of electromagnetic stirring (EMS) on carbon segregation of bearing steel concasting billet are illustrated in **figure 1** and **figure 2**. The results showed that the carbon segregation ratio (C/C_0) in billet was about 0.92–1.10 (C is the carbon content of segregation area, C_0 is the carbon content in steel sample taken from ladle). Although the EMS stirring is suitable for improving carbon segregation, white band is observable. In addition, the positive carbon segregation was observed in the center of billet without EMS, and the negative carbon segregation was found in "white band".

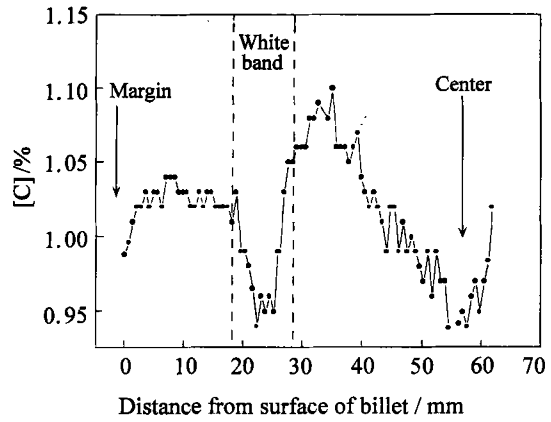

Figure 1 Carbon distribution in CC billet using electromagnetic strring (EMS).

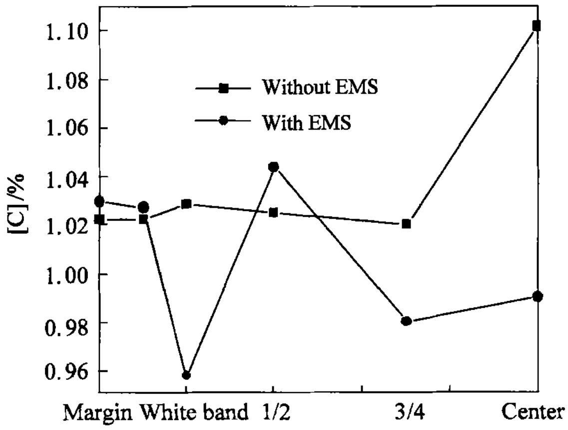

Figure 2 Carbon distribution in CC billets with and without EMS.

3.5 Fatigue life

Fatigue test data were treated by Weibull's method of statistical analysis. The contact fatigue life of thrust type test for different processes is tabulated in **table 4**.

Table 4 Fatigue life of thrust type testing specimens

Process	Rating life L_{10} / $\times10^5$	Median life L_{50} / $\times10^5$	Weibull ratio α	Oxygen content / $\times10^{-6}$	Testing Institute
EAF	39.4	285.9	0.95	28.6	Daye Steel Research Institute
IC	124.0	629.1	1.16	8.2	
ESR	171.6	803.8	1.22	18.6	
IC	2.36	4.50	2.92	10.6	Central Iron and Steel Research Institute
CC	3.19	8.33	1.97	11.0	

4 Discussion

4.1 Refining and oxygen content

The amount of oxide inclusion in steel decreases with decreasing the oxygen content in steel. Generally speaking, there are two kinds of method to remove the inclusions by aluminum deoxidation: up-floating of inclusion in steel and filtering of liquid steel. The latter, however, is hardly used in commercial production. There are a lot of refining units with which the inclusions are floated up by stirring the liquid steel [3]. There are many deoxidation elements in liquid bearing steel. Most oxygen in steel exists in the form of inclusions, and the soluble oxygen of liquid steel after aluminum deoxidation is very low, normally 2×10^{-6} ~3×10^{-6}. In this case, it is not feasible to decrease the oxygen content in steel further by carbon deoxidizing under vacuum, and the inclusion up-floating by stirring becomes the important measure to produce the clean low-oxygen steel. The less oxygen existed in steel prior to vacuum degassing, the less would be expected after the vacuum treatment. In order to make the inclusion floating up sufficient to obtain clean low-oxygen steel, the metallurgical parameters during refining are controlled by computer with argon stirring for 30 to 40 min under the given power, then soft stirring for 5 min. As shown in table1, a total content of oxygen less than 10×10^{-6} was obtained by the ladle refining process.

4.2 Effect of carbon segregation in CC bearing steel on fatigue property

The rating life L_{10} is indicative of the contact fatigue property of steel. It reflects the quality of bearing steel very well. The Weibull slope is an important parameter judging the stability of quality. When the value of the slope is greater than 1.0, the stability of quality is high. It can be seen that L_{10} of bearing steel produced by continuous casting process is 1.35 times over that of ingot casting steel as shown in table 4. The fatigue life testing results show that when carbon segregation (C/C_0) of bearing steel produced by continuous casting process is from 0.92 to 1.10 (C is the carbon content of segregation area, C_0 is the carbon content in steel sample taken from ladle), the white band and central negative carbon segregation have little effect on the fatigue property, which is consistent with the experiment results of Japanese Sanyo Special Steel Company and Kobe Steel Company [3–5]. By observing spheroidizing annealing, quenching and tempering structures in continuous casting steel white band and central segregation area, we didn't find any difference with the structure of other parts of matrix. In addition, the hardness tests revealed that hardness values are rather uniform.

4.3 Oxygen content, inclusion and fatigue life

Research work shows that nonmetallic inclusion is one of the most important factors influencing the fatigue life of bearing steel. The requirement of high cleanliness for bearing steel is therefore the common demand. As the continuous casting process can take protected casting technology, get rid of the pollution by runner brick and has higher cooling speed, the fatigue life of CC steel can be higher than that of IC steel because of its low-oxygen and dispersed inclusions. The content of oxygen is indicative of the cleanliness of steel, but it is not a complete representation of quality for bearing steel [2]. The size of inclusion and its dispersion are very important. Generally, the failure of a bearing originates from a big inclusion among the inclusions. This opinion has been proved with the high fatigue life of ESR steel. Although the amount of inclusion and oxygen in ESR steel is higher than that of Ladle refining steel (table 4), the fatigue life of ESR steel is higher than the latter because of its fine and dispersed inclusions.

5 Conclusions

(1) The fatigue life of ladle refined steel with less than 10×10^{-6} oxygen and fine dispersed inclusion is three times as high as that of EAF steel. Bearing steel with oxygen content less than 5×10^{-6} can be produced by the ladle refining process.

(2) Although the central porosity and segregation can be improved when applying EMS to CC process, the "white band" and central negative carbon segregation are unavoidable. The maximum oxygen content in steel produced by concasting process is 13×10^{-6} with an average oxygen content of 9.3×10^{-6}, the carbon segregation (C/C_0) in casting billet is 0.92–1.10 and the fatigue life of concasting steel is equal to that of ingot casting steel.

(3) Although the oxygen and inclusions contents of ESR steel are higher than those of ladle refining steel, the fatigue life of ESR steel is higher than that of the latter because of its fine and well dispersed inclusions.

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