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Isothermal heat treatment of a bearing steel for improved mechanical properties

Chao Huang [a], Chaolei Zhang [a], Le Jiang [b], Yong Yang [a], Yazheng Liu [a, *]

[a] *School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[b] *Wafangdian Bearing Group Co Ltd, Dalian 116300, China*

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ABSTRACT

This study aims to determine the optimum parameters of isothermal heat treatment process for a new bearing steel through orthogonal experiment method, and obtain improved mechanical properties of interest. Following the orthogonal experiment, a verification experiment with isothermal temperature lower than martensite start temperature was conducted, and microstructure evolution in isothermal process was investigated. The steel, produced by austenitizing at 880 °C for 0.5 h and isothermal holding at 200 °C for 6 h, has excellent combination of mechanical properties, at the same time has fine and uniform microstructure. Under the optimum heat treatment condition, the impact strength and the hardness value increase by 28.8% and 5.2% respectively, while the tensile strength only decreases by 3.7%, compared with those of the conventional process.

1. Introduction

GCr15SiMn steel is the commonly used material for roller bearing applications of large shield machine [1]. But for bearing with the diameter no less than 6 m, GCr15SiMn steel is not a good choice because of inadequate hardenability. Hence ZWZ12 steel, with better hardness, strength and hardenability on account of its higher contents of Cr and Mo [2,3], was chosen. ZWZ12 steel, corresponding to the Swedish SKF5 steel and Germany X82WMoCrV6-5-4 steel [4], is an advanced high carbon chromium bearing steel developed by a Chinese company in 2012. The production procedure of ZWZ12 steel is: EAF melting → vacuum degassing → molding → forging (Φ470 mm) → turning → electroslag remelting (3.5 t, Φ590 mm) → blooming (190 mm × 190 mm) → rolling (Φ75 mm) → forging → spheroidizing annealing → rough turning → austempering → smooth turning → grinding → assembling. With austenite start temperature at 755 °C, austenite finish temperature at 845 °C and martensite start (M_s) temperature at about 220 °C [5], ZWZ12 steel is finally austempered (isothermal holding above M_s temperature) at 240 °C for 6 h to develop fully bainitic microstructure in the practical use, but the hardness can't meet the requirement (no less than 60 HRC).

Studies show that steels with duplex microstructure have better performance than those with single [6,7]. It is illustrated that steels produced with martensite - bainite quenching process (firstly quenching and isothermal holding below M_s temperature, after that isothermal holding above M_s temperature) have better mechanical properties than those with bainite – martensite quenching process (firstly isothermal holding above M_s temperature and then quenching below M_s temperature) [8,9], because pre-formed martensite accelerates the subsequent nanobainite transformation [10]. Zuoren Xu [11,12] reported that isothermal quenching process, with isothermal temperature below M_s temperature, can develop a duplex martensitic + bainitic microstructure and enhance the toughness remarkably without reducing the strength. Because the strength of the lower bainite is close to that of the martensite, while the toughness is much better. Both martensite - bainite quenching process and isothermal quenching process have broad application prospect.

Therefore, the present study attempts to determine the optimum isothermal heat treatment process window (temperature, time) for ZWZ12 steel to develop a duplex martensitic + bainitic microstructure and achieve improved mechanical properties of interest.

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* Corresponding author.
E-mail address: lyzh@ustb.edu.cn (Y. Liu).

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2. Experimental

The experimental material was spherodized annealed ZWZ12 bearing steel with a nominal composition of 1.00%C, 0.25%Si, 0.69% Mn, 1.70%Cr, 0.43%Mo, 0.03%Ni, 0.003%P, 0.001%S and balance Fe (in wt.%). The heat treatment was designed by using orthogonal experiment method with L_9 (3^4) type orthogonal form where the following three factors were analyzed: austenitizing temperature (factor A), isothermal temperature (factor B) and isothermal time (factor C), as shown in Table 1. For each factor, three levels were designed, such as the austenitizing temperature are 840 °C, 860 °C, and 880 °C. The samples were austenitizing in air followed by direct transfer (with no time lag) to alkali bath (37% NaOH + 63% KOH, wt %) [13] furnaces for isothermal holding before air-cooled to room temperature. A verification experiment was conducted subsequently based on the optimum isothermal process obtained from the orthogonal experiment. In addition, microstructure evolution in isothermal holding process was investigated through samples with isothermal time of 0.25, 0.5, 1, 1.5, 2, 3, 4, 5 and 6 h at 200 °C followed by air cooling.

The heat-treated samples were mechanically polished and etched with 4% nital solution and color metallography reagents (reagent 1 is 24 g Sodium thiosulfate and 2.4 g cadmium chloride and 3 g citric acid in 100 ml water [14]; reagent 2 is 1:1 mixture of 1% sodium thiosulfate solution and 4% picric acid solution [15]). The polished and etched samples were subjected to a detailed microstructural investigation using Zeiss Axio Scope A1 optical microscope (OM) and Qutanta FEG 450 field emission scanning electron microscope (FE-SEM). X-ray diffraction (XRD) studies allowed determination of volume fraction of the retained austenite in the course of isothermal heat treatment. The quantitative measurement of bainite and carbide was carried out with image analysis software Image Pro Plus. Hardness and microhardness were measured using TH320 Rockwell and Leica VMHT 30M Vickers hardness tester. Tensile and unnotched impact strength of samples with appropriate dimensions and geometry were measured using WAW-Y500C tensile tester and JB-30B room temperature impact tester, respectively.

3. Results and discussion

3.1. Isothermal orthogonal experiment

Based on the L_9 (3^4) type orthogonal form, nine experiments were carried out and mechanical properties, including tensile strength, yield strength, elongation, impact strength and hardness, under different heat treatment conditions were obtained. Mechanical properties and requirements of the program are summarized in Table 2. Relations between factors and indexes were obtained according to the range analysis method, as shown in Fig. 1. The range value indicates the significance of the factor's effect, and a larger range value means the factor has a stronger impact on the specific mechanical property [16]. Apparently isothermal temperature is the most significant influential factor on tensile strength, yield strength, elongation, impact strength and hardness. Meanwhile, isothermal time has a secondary influence on tensile strength, elongation and hardness, and austenitizing temperature also has an influence on yield strength and impact strength. Indexes reach the maximum values at these combinations based on relations between factors and indexes: tensile strength (A2B2C2), yield strength (A1B3C2), elongation (A1B3C2 or A2B3C2), impact strength (A1B3C1 or A1B3C2), and hardness (A3B1C3).

Among the mechanical indexes of ZWZ12 bearing steel, all the tensile strength of the experiments are much higher than that specified in the program, while only four of the experiments meet the hardness requirement. In this instance, the hardness is the key index limiting the comprehensive mechanical properties. Therefore, hardness was set as the primary index for the evaluation of heat treatment quality in this study. Hardness reaches the maximum value at the combination of A3B1C3, so austenitizing temperature and isothermal temperature were set as 880 °C and 200 °C, respectively. Because there is little difference in hardness value when the steel is isothermally treated for 8 h and 6 h, isothermal time was set as 6 h. Thus the optimum heat treatment process was determined: austenitizing at 880 °C, and isothermal holding at 200 °C for 6 h.

3.2. Verification experiment

The experiment was repeated under the optimum process conditions (austenitizing at 880 °C, and isothermal holding at 200 °C for 6 h) to confirm that they truly optimized the comprehensive mechanical properties. Results with tensile strength of 2236 MPa, yield strength of 1363 MPa, elongation of 2.3%, unnotched impact strength of 134.44 J and hardness of 61.2 HRC were obtained, meeting the requirements of the program.

3.3. Microstructure evolution in isothermal process

Color metallography of Fig. 2 shows that the uniformity of the microstructure is improved, and lower bainite volume fraction (f_B) increases (refer to Table 3) as the isothermal time increases. Color difference, resulting from the composition difference, shows the uniformity of the microstructure (Fig. 2(a–c)). Isolated fine needles of lower bainite grow up gradually and start to form in hassocks when isothermal holding for 2 h, and bainite becomes mostly in connected hassocks after isothermal holding for more than 4 h (Fig. 2(d)–(f)). Isothermal time should be no less than 6 h to obtain uniform microstructure when the steel is isothermally treated at 200 °C.

Fig. 2(d) also shows that microhardness varies significantly in different parts of the same microstructure developed after isothermal holding at 200 °C for 2 h with the same (880 °C, 0.5 h) prior austenitizing routine. The light blue and harder region (894.4HV) is martensite while the yellow/brown and softer areas (753.7 HV) represent bainite. Similar variation is recorded in the microstructure obtained by similar isothermal holding at 200 °C for different times. Table 3 also shows that the hardness decreases as

Table 1
Factors and levels of the heat treatment experiments for ZWZ12 bearing steel.

Level	Factor		
	A	B	C
	Austenitizing temperature/°C	Isothermal temperature/°C	Isothermal time/h
1	840	200	4
2	860	220	6
3	880	240	8