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Microstructure and phase transformation of wear resistant ductile iron grinding balls by continuous cooling process

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ABSTRACT

The hardenability of wear resistant ductile iron austenitized at different temperatures was analyzed by Jominy end-quenching test, and continuous cooling transformation (CCT) curves were determined by Gleeble 1500D. The temperature variety curves were recorded by thermocouples during the test, and the cooling rate curves were obtained. It was indicated that there were significant influences of austenitizing temperature and Jominy distance (D_J) on the cooling rate. All specimens had undergone three different heat transfer mechanisms including film boiling mechanism, nucleate boiling mechanism and natural convection mechanism. Meanwhile, the cooling rate also had a distinct influence on the microstructure characteristics of ductile iron. The results of hardness test and microstructure observation indicated that the specimen austenitized at 830 °C had the most suitable hardness distribution, with high hardness on the quenching end and high toughness inside. That means that the grinding balls present function gradient characteristic can be obtained after continuous cooling. In addition, as to the specimen austenitized at 780 °C, the hardness was lower for the partially austenitized mixture microstructure. As to the specimen austenitized at 880 °C, the coarsing of the microstructure occurred, which affected the mechanical properties significantly.

1. Introduction

The ductile iron has been used as an important engineering material for years because of its attractive properties such as, good ductility, high fatigue strength and fracture toughness, etc [1–3]. In addition, the diameter of the ball mill has increased than before obviously, for improving the efficiency of ore crushing [4,5]. The world's largest ball mill has reached 13 m in diameter at present, and the service condition of high hardness and impact load requires higher toughness and hardness of grinding ball. Benefiting from the multiple advantages, ductile iron is endowed a potential ability to adapt to service condition in ball mill [6,7]. Especially as the bainite-martensite ductile iron, with better mechanical property, was considered to be a substitution of the traditional grinding ball such as low chrome white cast iron and low manganese steel [8]. At present, there are two common heat treatment processings for bainite–martensite ductile cast iron. One is isothermal quenching process [9], in this way, the ductile iron named as austempered ductile iron (ADI) is obtained; The other is continuous cooling process [10], which is more convenient, economical and practical.

Up to now, numerous studies about ductile iron focus on the influence of chemical component or heat treatment process, which are the critical factors affect the microstructure and mechanical properties of ductile iron. Yang [11] has invented a new austempering process for austempered ductile cast iron (ADI), and found that the novel two-step process has resulted in improved microstructural variables in the ADI matrix, and higher hardness, yield strength and tensile strengths, but lower ductility compared to the conventional single-step austempering process; Murcia [12] studies the fabrication of dual matrix structures (DMS) ductile cast irons with martensitic and bainitic structures in the as-cast condition, and found that mechanical behavior of the material was improved obviously after heat treatment; Han [13], has studied the effects of austempering temperature and time on scuffing behavior of austempered Ni–Mo–Cu ductile iron. Other methods to enhance the properties of the ductile iron were also discussed; Li [10] has studied the chemical composition range and the heat treatment of austenitic–bainitic ductile iron produced by continuous cooling, results show that the mechanical properties of austenitic–bainitic ductile iron produced by continuous cooling are close to those of isothermally treated iron; Sun [14] has obtained bainitic-martensitic-austenitic ductile iron by continuous cooling, studied the wear behavior and wear mechanism under impact load. Peng [15] has investigated the influence of boron on the

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microstructure and mechanical properties of carbide austempered ductile iron (CADI); Ghaderi [16] examined the effect of graphite morphologies on the tribological behavior of austempered cast iron. Podgornik [17] improved the wear resistance of ductile iron through local surface reinforcement. Although numerous previous studies have been performed about the heat treatment process and wear behavior of ductile iron, there is still no in-depth research on the microstructure characteristics of grinding ball with large diameter. As to the grinding ball with 110 mm in diameter, the matrix and mechanical properties are very hard to guarantee, for the restriction of material's hardenability. So, more attention should be paid on the hardenability of ductile iron in the as-cast condition.

In this study, Jominy end-quenching test was applied to examine the hardenability of grinding ball. The standard specimens were cut out of the grinding ball along the radial direction. Thermocouples installed on the specimens were used to record the variation temperature values during the quenching operation. The CCT curves of ductile iron were obtained and the effect of different austenitizing temperatures on the proportion of microstructure was studied. The main goal of this paper is to provide an increased understanding of grinding ball hardenability and the relationship between microstructure evolution and cooling rate.

2. Materials and methods

C, Si and Mn, the main alloy elements in ductile iron, have the largest influence on the mechanical properties and cast-ability. High carbon content can improve the graphitizing ability and sphericize of graphite. However, the excessive carbon content causes more nodulizer consumption, a large extent of graphite floating, and a decrease in mechanical properties [18]. Proper silicon content can prompt graphitizing, prevent carbide from precipitating, and decrease the austenite stability. It also reduces the grain size, promotes bainite transformation and increases the toughness [19]. The adding of manganese can improve the hardenability, and decrease the manufacturing cost for its cheap price in China. Manganese has more affinity with carbon than Fe, so it can prevent carbon from diffusing and precipitating [20].

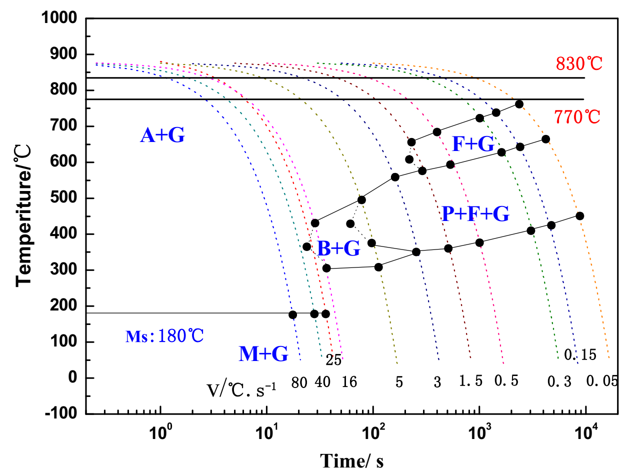

Fig. 3. CCT curves of ductile iron.

Table 1
Chemical composition of the wear resistant ductile iron (wt%).

Element	C	Si	Mn	P	S	Mg	Re
Weight%	3.5	3.3	3.0	< 0.1%	< 0.04%	0.038	0.045

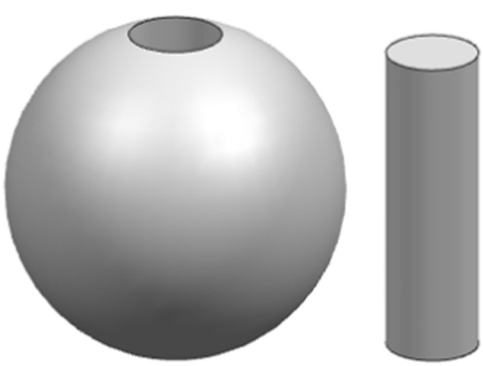

Fig. 1. The cylindrical bar cut from grinding ball.

Table 2
Label of specimens of Jominy end-quenching tests.

Specimen	Temperature (°C)	D_J (mm)
A-1	780	2
A-2	780	5
A-3	780	10
A-4	780	20
A-5	780	50
B-1	830	2
B-2	830	5
B-3	830	10
B-4	830	20
B-5	830	50
C-1	880	2
C-2	880	5
C-3	880	10
C-4	880	20
C-5	880	50

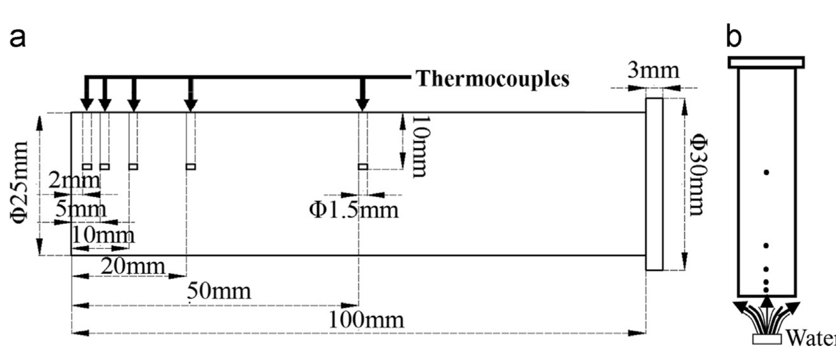

Fig. 2. (a) Size of standard Jominy specimen and locations of thermocouples and (b) Cooling of Jominy test.