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Mechanical properties and rolling-sliding wear performance of dual phase austempered ductile iron as potential metro wheel material

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ABSTRACT

Dual phase austempered ductile iron (dual phase ADI) was produced through intercritical austempering with various partially austenitizing temperatures. Partial austenitization within the intercritical interval has a profound influence on the amount and morphology of microstructure in dual phase ADI. The influence of partially austenitizing temperatures on the mechanical properties and rolling-sliding wear performance of dual phase ADI were also investigated. The results show steady increases in the tensile strength and yield strength with increasing partially austenitizing temperature, while the opposite behavior is observed for elongation. The optimum combination including ultimate tensile strength of 746 MPa, impact toughness of 125 J and elongation of 14% is obtained in the dual phase ADI partially austenitized at 810 °C, which is composed of 20% proeutectoid ferrite and 80% ausferrite constituent. Wear behavior could be understood from the manner the hardened layer fragmented and detached. The main wear mechanism under air cooling condition is delamination due to subsurface deformation. Wear rate decreases as matrix hardness increases. According to the results of mechanical and wear tests, dual phase ADI partially austenitized at 810 °C demonstrates superior wear performance as well as relatively reasonable mechanical properties, suggesting the potential of this material for application in metro wheels.

1. Introduction

Austempered ductile iron (ADI), combining excellent ratio of strength to weight [1], good fatigue strength [2], excellent wear resistance [3–5], high fracture toughness [6,7] and excellent design flexibility [8], has been used extensively in many structural applications, such as automotive components, gears, earth moving machinery and rail equipment [9–11]. The ADI consists of an ausferrite (AF) matrix microstructure, characterized by the existence of bainite ferrite (BF) and high carbon retained austenite (RA). The heat treatment responsible for the specific microstructure involves complete austenitization followed by austempering at a temperature ranging from 260 °C to 400 °C. During austempering treatment, ductile iron undergoes a two-stage transformation process [12]. The martensite from the stage I reaction and carbide from the stage II reaction are unfavorable for ductility and toughness. Thus, the optimum combination of strength and ductility in ADI is obtained within the time period between the completion of stage I and the onset of stage II, referred as the 'process window' [13].

However, the large amount of austenite in conventional ADI usually results in much work-hardening of materials and will deteriorate the machinability of ADI. Furthermore, absence of proeutectoid ferrite (PF) in conventional ADI limits the ductility of ADI. To overcome the limitations of conventional ADI, a new type of ductile iron, called 'dual phase ADI', has become an active focus of research and manufacturing [14–18]. The dual phase ADI consists of different amounts and morphologies of AF constituent (conventional ADI microstructure) and PF constituent, which can be achieved by intercritical austempering [19,20]. The special heat treatment is a process wherein ductile iron is partially austenitized within the intercritical interval (delimited by the upper and lower critical temperatures [21]) where graphite, ferrite and austenite co-exist, followed by an austempering step. It was noted that the position and amplitude of the interval changes with the chemical composition [22]. Additionally, dual phase ADI could provide a wide range of mechanical properties as a function of the relative proportion of PF and AF constituents, thereby replacing ductile iron with other matrices [23]. Therefore, dual phase ADI will be appropriate for new applications in the critical parts, where a combination of high strength and ductility is a pressing requirement.

With regard to research on the optimization of wheel materials,

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designers should balance the cost, weight, wear resistance, noise reduction and rolling contact strength [24]. Conventional ADI, with higher damping capacity and lower density, is suitable as an alternative material for railcar wheels [25–27]. Correspondingly, dual phase ADI, which exhibits much greater ductility and machinability than conventional ADI, may be applied to metro wheels, which demand lower rolling contact strength due to the working conditions of lower speed and lighter weight. Considering the application of dual phase ADI as a substitute for steels in the field of metro wheels, it is thus crucial to investigate its wear performance matched with conventional rail steel. The reason is that metro wheel materials are limited in service by adhesive wear and rolling contact fatigue wear, which are the main damage types of wheel/rail [24]. Many wear investigations concerning ductile irons have been conducted previously. Sahin et al. [28] studied the abrasive wear behavior of ADI with dual matrix structures and found that wear resistance increased with increasing AF volume fraction or decreasing austempering time. Bedolla-Jacuinde et al. [3] analyzed the wear resistance under dry sliding conditions of an ADI microalloyed with different amount of boron and concluded that both specific wear rate and friction coefficient increased slightly with the boron content due to the lower hardness obtained through this element. Zhang et al. [27] conducted rolling-sliding wear tests of ADIs with three strength grades matched with conventional rail steel. The results revealed that the increase of subsurface hardness was due to work-hardening and strain-induced transformation of retained austenite to martensite and the main wear mechanism was delamination.

However, no efforts have been so far made to investigate the dry rolling-sliding wear performance of dual phase ADI matched with conventional rail steel, which is an important consideration for designers of metro wheels. Therefore, the purpose of this investigation was to study the influence of intercritical austempering with different partially austenitizing temperatures on the mechanical properties and rolling-sliding wear performance of dual phase ADI. In addition, microstructural evolutions during intercritical austempering were characterized using an optical microscope (OM), X-ray diffraction (XRD), and a scanning electron microscope (SEM). Meanwhile, the fracture surface, wear behavior as well as wear mechanism of dual phase ADI were discussed in detail.

2. Experimental procedure

As-cast alloyed ductile iron with the chemical composition, displayed in Table 1, was prepared by induction melting and cast into 25 mm Y-blocks. As shown in a previous study, the material consisted of pearlite and PF constituents surrounding graphite nodules with 85% nodularity, and had a yield strength of 372 MPa, tensile strength of 676 MPa, and elongation of 8.6%. The preliminary investigation was performed to determine the intercritical interval and study the influence of partially austenitizing temperatures on the fraction of PF constituent. For this purpose, samples of 40 × 25 × 10 mm, machined from the bottom section of Y-blocks, were annealed for 60 min around the calculated intercritical interval, which was estimated to range from 770 °C to 799 °C using empirical equations [29,30]. The samples were then quenched in water at room temperature. The fraction of PF constituent was determined with the assistance of Image-Pro Plus software.

Based on the results of preliminary investigation, heat treatment cycles employed to produce dual phase ADI consisted of a first step of partial austenitization, in which samples of 155 × 40 × 12.5 mm were held at temperatures within the actual intercritical interval, followed by an austempering step of 350 °C in a salt bath containing 50% KNO_3 + 50% $NaNO_3$, as shown in Fig. 1. The austenitizing temperatures employed were 770, 790, 810, and 830 °C, respectively. In all cases, austenitizing and austempering times were both 60 min. The samples were labeled according to matrix structure and partially austenitizing temperature and coded as D770, D790, D810, and D830, respectively. For reference, conventional ADI was also produced through complete austenitization and coded as C900. After the heat treatment above, microstructural characterization, mechanical properties and rolling-sliding wear performance were investigated to evaluate the potential of dual phase ADI as metro wheel material. For this reason, metallographic specimens, tensile specimens (gauge length Φ5 × 30 mm), Charpy impact specimens, and rolling-sliding wear specimens were machined from the heat-treated samples, respectively.

Table 1
Chemical composition of as-cast ductile iron (wt%).

Element	C	Si	Mn	P	S	Cu	Ni	Mg
Composition (%)	3.62	2.67	0.13	0.05	0.01	0.62	0.63	0.04

*The carbon equivalent of the alloyed ductile iron was 4.51.

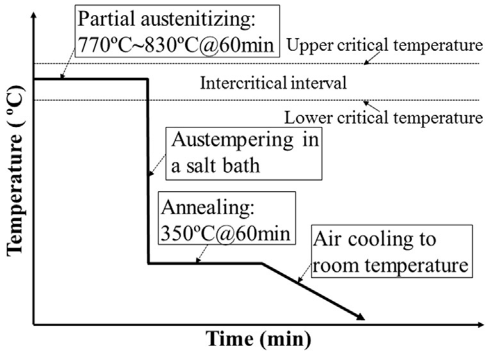

Fig. 1. Heat treatment cycles employed to produce dual phase ADI.

Metallographic specimens were examined by OM (Axio Cam MRc5) and SEM (ZEISS SUPRA 55) after being ground, polished, and etched with 4 vol% Nital. The fraction of PF constituent was evaluated from the results of preliminary investigation. It should be noted that graphite was not taken into consideration when characterizing the fraction of reported constituents. The fraction of RA constituent was determined using the direct comparison method based on the typical intensities of austenitic peak and ferritic peak [31,32]. XRD was carried out using monochromatic copper Kα radiation at 40 kV and 40 mA. A Bruker Phaser II diffractometer was used to scan at the 2θ angle, ranging from 20° to 90° with an angular speed of 2°/min. The profile was then analyzed using Jade 5 software to obtain the peak positions and the integrated intensities for the (111), (200) and (220) planes of FCC and the (110), (200) and (211) planes of BCC. Additionally, the fraction of BF constituent was obtained by subtracting that of RA constituent from that of AF constituent. The carbon content of the austenite was determined by the equation [33]:

$$a_\gamma = 3.555 + 0.044C_\gamma$$

where a_γ is the lattice parameter of austenite (Å) and C_γ is the carbon content (wt%). The (111) planes of austenite were used to estimate the lattice parameter.

Tensile tests were conducted following the specifications given by ASTM E8/E8M-2009 [34] using a universal testing machine (20-t SANS) with a cross-head speed of 1 mm/min at room temperature. The tensile properties, including ultimate tensile strength (UTS), yield strength (YS) and elongation (E_f), were calculated as the averages of three tests. After the test, the fracture surface was analyzed by SEM to characterize the fracture mechanisms. Furthermore, Impact toughness was measured based on the average of three unnotched Charpy impact tests. In addition, Vickers hardness of matrix structure was examined with an MH-5 tester applying a load of 490 mN ($HV_{0.05}$). Average values were obtained based on 10 measurements.

Based on Chinese standard GB/T 12444.1-1990 [35], dry rolling-sliding wear tests were conducted on the disc-on-disc configuration,