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Rolling contact fatigue resistance of austempered ductile iron processed at various austempering holding times

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ABSTRACT

The rolling contact fatigue resistance of austempered ductile iron (ADI) produced at various holding times was evaluated by using a twin-disk rolling configuration rig. The resulting fatigue life of ADI samples was compared with that of conventional quenched and tempered (Q&T) ductile iron samples with the same chemical composition. It was found that the macro hardness of ADI samples decreased and the fatigue life became shorter for longer holding time. For similar macro hardness, ADI samples had higher fatigue resistance as compared with Q&T ductile iron samples. Optical microscopy and scanning electron microscopy indicated that the graphite nodules acted as crack nucleation sites for the ductile iron. The cracks propagated towards either the surface or adjacent graphite nodules until the formation of pits or spalls occurred. The excellent fatigue resistance of ADI samples could be attributed to the increase of surface hardness which was caused by the strain induced transformation of retained austenite into martensite. By using X-ray diffraction, the difference of retained austenite present in the wear track and off the wear track ranged from 4.42% to 26.15%.

1. Introduction

Austempered ductile iron (ADI) is produced by an iso-thermal heat treatment process. In recent years, it becomes a good candidate material to replace steel castings and forgings in diverse applications such as automotive, manufacturing and agricultural industries [1,2]. Excellent mechanical properties of ADI can be achieved due to its unique ausferritic structure consisting of acicular ferrite and carbon-enriched austenite. Austempering temperature, holding time, chemical composition and cooling rate significantly influence the mechanical performance of ADI [3,4].

In many mechanical systems such as gears, cam and followers, and connecting rods, contacting components subjected to cyclic load or pressure are frequently used. Rolling contact fatigue damage is often the main failure mechanism for these components [5]. Several methods have been proposed to reduce the possibility of fatigue failure such as improving the component cleanliness level and advanced surface treatments [6,7]. However, appropriate material selection is required to extend the service life for rolling elements. The use of ADI is a possible alternative to conventional materials used in these applications.

The study of contact fatigue resistance of ADI material has attracted much attention in the last two decades. Dommarco et al. [8] found that ADI had excellent resistance to crack propagation but weak resistance to crack nucleation by using a ball-rod rolling contact fatigue tester. Brunetti et al. [9] studied the effects of sample surface preparation on endurance life of ADI. They found that ground ADI samples had a shorter lifetime than that of polished samples. As compared with polishing processes, tiny cracks were generated after a grinding process, which acted as stress raisers and reduced the fatigue resistance.

The previous research studies generally focused on the contact fatigue resistance of ADI produced by only one austempering temperature and holding time. However, different combinations of austempering temperature and holding time can produce differences in microstructure which significantly affect the mechanical properties of ADI. In this research, the rolling contact fatigue resistance of ADI produced by the same austempering temperature but different holding times was evaluated by using a twin-disk rolling configuration rig. The results were compared with traditional quenched and tempered (Q&T) ductile iron with the same chemical composition. The morphology of the worn surfaces were observed by optical microscopy and scanning electron microscopy (SEM) and the percentage of retained austenite was detected by X-ray diffraction (XRD) to understand the potential failure mechanisms.

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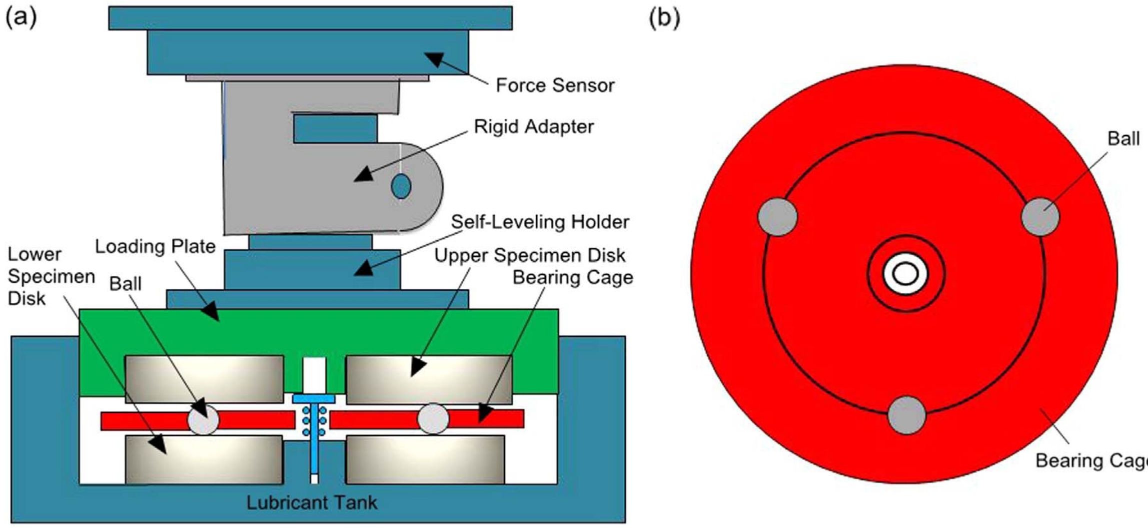

Fig. 1. (a) Sectional View of Twin-disk Rolling Fixture. (b) Top View of Bearing Cage and Three Balls.

2. Experimental procedure

2.1. Test equipment

Rolling contact fatigue tests were carried out by using a universal mechanical tribometer (UMT-3) with a twin-disk rolling fixture. A schematic view of this twin-disk rolling fixture is shown in Fig. 1. This bearing assembly consists of a loading plate, upper sample disk, bearing cage and lower sample disk. The balls were held at an angle of 120° from each other by the bearing cage between the upper and lower specimens. The loading plate was used to transfer the load to the bearing assembly. During the test, the lower disk rotated and the upper disk and loading plate were held stationary. A force sensor and self-leveling holder were equipped on the top of the system. For these rolling contact fatigue tests, 3 balls rolled without any sliding motion between the two sample disks. An acoustic emission sensor was employed to detect the onset of fatigue failure, which occurred when pits or spalls formed inside the wear track.

Macro and micro hardness were measured by using a Rockwell hardness tester and a micro Vickers hardness tester with a load of 9.8 N and testing duration of 10 s. A 3D optical profilometer was used to examine the roughness of the sample disks. Optical microscopy and SEM were used to observe the microstructure and surface/subsurface damage.

2.2. Chemical composition

The chemical composition of the ductile iron samples is shown in Table 1.

2.3. Heat treatment process

ADI samples with an outer diameter of 63 mm, inner diameter of 27 mm and a thickness of 5 mm were used as counter disks. The original microstructure of the ductile iron is graphite nodules uniformly surrounded by pearlite, see Fig. 2.

Table 1
Chemical Composition of Ductile Iron Samples (mass%).

C	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**Mo**	**Cu**
3.54	0.18	0.29	0.015	2.2	0.04	1.58	0.01	0.73
Al	**V**	**Nb**	**Ti**	**Co**	**Sn**	**B**	**Mg**	**W**
0.023	0.017	0.001	0.007	0.021	0.009	ND	0.046	0.008

ND: Not determined due to the resolution of apparatus.

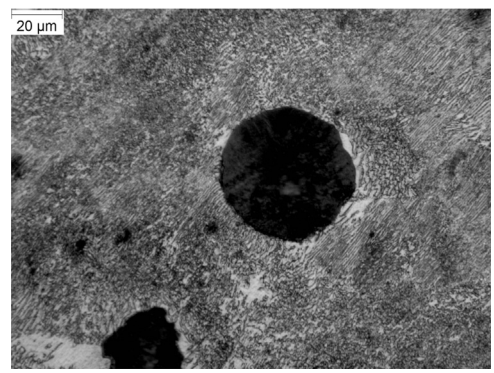

Fig. 2. Original Microstructure of Ductile Iron before Heat Treatment.

In the preparation of ADI samples, five austempering holding times were selected based on the results from previous study [10]. In the previous study, longer holding times provided more time for carbon atom diffusion to coarsen the ferrite platelets. At the same time, the volume fraction of high carbon content austenite increased which resulted in a decrease in the volume of martensite in the ADI matrix when the samples were cooled to room temperature. This decrease in volume of martensite resulted in a decrease of hardness with holding time.

In this research, the raw material was first austenitized at 900 °C for 30 min in a salt bath furnace, and then quickly transferred to another pre-heated salt bath furnace for an austempering process at 275 °C for 15 min, 30 min, 45 min, 60 min or 120 min. Oil quenching was used to cool the sample disks to room temperature.

In the traditional quenched and tempered heat treatment process, raw samples with the same chemical composition as used for the ADI specimens were austenitized at 900 °C for 30 min and then water quenched. A temperature of 160 °C for 60 min was selected for the tempering process. Higher tempering temperatures would cause undesirable softening. After the tempering step, samples were cooled by water quenching.

2.4. Test specimen

The disk samples were ground and polished to the range of 0.2–0.4 µm (arithmetic roughness, Ra). The balls were made of SAE 52100 bearing steel with a diameter of 4 mm, hardness of 60HRC and Ra roughness of 0.1 µm. The lubricant used was Mobil-10W-40 fully