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Study of the effects of austempering temperature and time on scuffing behavior of austempered Ni–Mo–Cu ductile iron

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ABSTRACT

Scuffing can occur in various engineering components, including engine cylinders and liners, camshafts, crankshafts, and gears. Austempered ductile iron (ADI) is finding increasing application in these components due to its self-lubricating characteristics and excellent mechanical properties. The objective of this research is to study the scuffing behavior of an austempered ductile iron material austempered at different temperatures and for varying periods of time. Rotational ball-on-disk tests were run with white mineral oil as the lubricant at two sliding speeds. A step load was applied until scuffing occurred. The scuffed specimens were studied using optical and scanning electron microscopy to determine their scuffing mechanisms. Improved scuffing resistance, as evidenced by a higher scuffing load, is related to a decreased hardness and higher level of retained austenite which produce a more ductile material.

1. Introduction

As noted by Qu et al. [1]: "The term 'scuffing' has been used to describe surface damage in various contexts throughout the field of engineering". Scuffing is associated with a sharp rise in friction and surface temperature, usually accompanied by a rise in noise and vibration [2,3]. There has been no general agreement on a definition for scuffing. This has, to a large extent, been due to the complexity of the process. However, one definition that has captured many of the features of scuffing is: "Scuffing is a form of sliding-induced contact damage to a bearing surface, usually associated with asperity-scale plastic deformation that results in localized and perceptible changes in roughness or appearance without significantly altering the geometric form of the part on which the damage occurs [1]."

Usually scuffing damage is catastrophic and not self-healing so that the scuffed part must be replaced. Scuffing may be delayed or prevented by selecting materials with appropriate microstructure and hardness. However due to the complexity of the scuffing process, there is a need to conduct a variety of experiments to better understand the scuffing mechanism, and to evaluate the influence of material microstructure and hardness on scuffing.

Austempered ductile iron (ADI) has recently appeared as a significant engineering material owing to its exceptional combination of high strength, ductility, toughness, machinability and wear and fatigue resistance [4]. The attractive properties are related to its unique microstructure that includes ferrite (α) and high carbon austenite (γ_{HC}), called ausferrite. This is different from the austempered steels where the microstructure involves ferrite and carbide. The products of ADI can be molded, which allows cost reduction compared to conventional steels. Castability removes unnecessary forging and assembly requirements saving cost and weight [5,6]. Therefore, it appears that ADI can be substituted for forged and cast steels in many engineering applications such as camshafts, crankshafts, and piston rings, as well as other applications in the rail and heavy engineering industries [5–7]. A two stage heat treatment is used for ADI, austenitization (815–950 °C) and austempering (230–400 °C) [4,7–9].

Mechanical properties of ADI vary over a wide range of values, mostly controlled by the microstructure which depends on the heat treatment parameters, such as the austenitizing and austempering temperature/times [4,9–11]. A significant number of studies have been carried out on the tribological behavior of ADI [12–19], but few studies have examined scuffing. Magalhães and Seabra [20] found that the properties of ADI may help it resist scuffing. However there is little published research dealing with the effect of both microstructure and hardness on the scuffing behavior of ADI.

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The objectives of the present investigation were to examine the effect of heat treatment schedules, and resulting microstructure and hardness of ADI, on its scuffing performance and to determine the mechanisms involved in the scuffing process.

2. Experiment details

2.1. ADI material and heat treatment

The ADI was an alloyed nodular ductile cast iron with a composition of 1.61% Ni, 0.11% Mo, 0.78% Cu, 3.76% C, 0.24% Mn, 2.51% Si, 0.057% Mg, and traces of S and P. This Ni–Mo–Cu ductile cast iron was initially heat treated in a salt bath at 890 °C for 20 min for austenitization, then quenched directly in another salt bath down to the austempering temperature of either 275 °C, 300 °C, 325 °C, 350 °C, or 375 °C for different periods of time, namely 10 min, 60 min, or 150 min. After austempering, the samples were immediately cooled in air to ambient temperature. The detailed heat treatment process is shown schematically in Fig. 1.

To determine the volume fraction of retained austenite for each heat treatment process, an X-ray diffraction (XRD) method was used with monochromatic Cr–Kα radiation (wave length λ=2.29 Å) at 20 kV and 20 mA. The recorded profiles were analyzed to obtain the precise diffraction peak positions and integrated intensities. The volume fraction of retained austenite was determined by the direct comparison method using the integrated intensities of the (200)$\alpha$and (211)α peaks of ferrite, and the (200)γ and (220)γ peaks of austenite [21,22].

2.2. Scuffing test

A ball-on-disk tribometer (shown in Fig. 2) was used to carry out the tests at room temperature. The ball sample was made of 52100 steel with a diameter of 7.94 mm and a hardness of 66 HRC. The ADI disk specimens had a diameter of 75 mm and a thickness of 10 mm. The disk surface was finished by grinding after the heat treatment, producing an average roughness of R_a = 0.399 μm. During the test, the rotational speed of disk is 700 rpm. The ball was located at two different radii, which resulted in two wear tracks and two linear velocities. One wear track had a diameter of 0.045 m and a linear velocity of 1.649 m/s, and the other one had a diameter of 0.037 m and a linear velocity of 1.356 m/s. The applied normal load was increased by 22 N every 120 s and the test was terminated when there was a sudden increase of the coefficient of friction, noise level and severe vibration, which usually -occurred simultaneously with the onset of scuffing. The load at this time was defined as the scuffing load. The friction force was measured with a strain gage mounted on the sample holder. The disk specimen was lubricated by white mineral oil with a viscosity of 53 cP at room temperature. All tests were repeated 4 times and the average coefficient of friction (COF) and scuffing load were recorded. Typically the coefficient of friction was approximately 0.1 before scuffing and increased rapidly to approximately 0.25 when scuffing occurred.

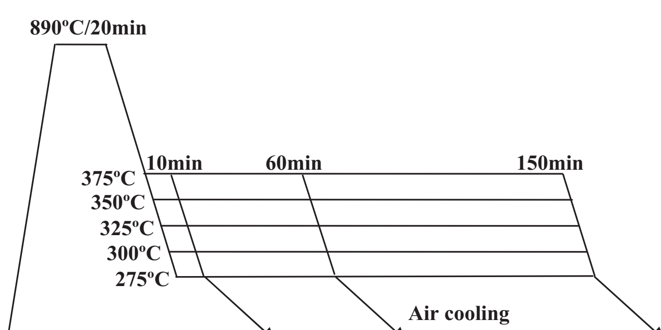

Fig. 1. Ni–Mo–Cu ductile cast iron austenitization and austempering process chart.

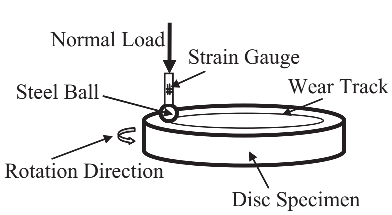

Fig. 2. Schematic view of the ball-on-disk test rig.

3. Results

3.1. Microstructure of austempered ADI

The microstructures of the ADI austempered at 5 different temperatures and 3 time periods are shown in Table 1. Distinct differences in microstructure were observed for different austempering temperatures and times. For short austempering times (10 min), the microstructure consists of nodular graphite and a very small amount of ausferrite (ferrite and austenite) in a martensitic matrix. Martensite was detected for all 5 austempering temperatures. With an increase in the austempering temperature, more ausferrite is developed and the fine needle ausferrite becomes coarser. For long austempering times (60 min, 150 min), the microstructure consists of nodular graphite in an ausferrite matrix without martensite. Long austempering times result in the martensite being transformed into high carbon austenite. The fine ausferrite needles grow larger with an increase in austempering temperature. A coarse feathery ausferrite is produced at the higher austempering temperatures, as shown in Table 1 (350 °C/60 min, 150 min and 375 °C/60 min, 150 min). Increasing the austempering temperature results in higher quantities and coarser ausferrite.

The measured volume fractions of retained austenite are shown in Table 2. It can be seen that the volume fraction of retained austenite is lower for the 10 min austempering time than for the 60 min and 150 min austempering times. The volume fraction of retained austenite is slightly higher for the 60 min austempering process than in the 150 min austempering time. This can be explained by a 2 stage transformation during the austempering process. In the first stage during the austempering process, austenite which was developed during the austenitization process, decomposes into ferrite (α) and carbon enriched austenite (γ_{HC}):

$$\gamma \rightarrow \alpha + \gamma_{HC} \tag{1}$$

If the material is austempered for longer times, then the carbon enriched austenite (γ_{HC}) further decomposes into ferrite and carbide:

$$\gamma_{HC} \rightarrow \alpha + carbide \tag{2}$$

It can be assumed that the 60 min duration had produced the highest amount of stable enriched austenite. When kept for a longer period (150 min), the 2nd stage process occurred, reducing the amount of stable austenite [4,7,10].

3.2. Hardness of austempered ADI

The influence of austempering temperature and time on the hardness of ADI is shown in Table 3. It is found that low austempering temperature and short time cause ADI to have high