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# Effect of sliding speed and contact pressure on the oxidative wear of austempered ductile iron

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The dry tribo-oxidative sliding wear of an ADI was investigated as a function of sliding speed and applied pressure, using a pin-on-disc apparatus. The wear rates, steady-state friction coefficients and contact temperatures were measured for each sliding conditions, and the acting wear mechanism were investigated by means of metallographic observations of worn surfaces and subsurface damaged regions. Two friction and wear regimes were identified. In the first one, at low sliding speeds (0.5–1 m/s), friction coefficient and wear rates were found to decrease with sliding speed and applied pressure. In the second one, at high sliding speeds (1.5–2.6 m/s), friction and wear were found to decrease with sliding speed but to increase with applied pressure. The observed behaviour and the transition from the low-sliding speed regime to the high-sliding speed regime were explained by considering the formation of a surface white layer that is controlled by the attainment of a critical flash temperature during sliding.


## 1. Introduction

Cast irons are characterized by an attractive combination of mechanical properties and economical and manufacture advantages. They are widely used in mechanical applications characterized by dry as well as lubricated sliding conditions. Typical examples are disk brakes, piston rings, cylinder liners and gears. In the past few decades, ductile iron has achieved increasing attention, since it combines high strength with good fatigue resistance and fracture toughness because of the presence of nodular graphite in its microstructure [1]. The properties of ductile iron can be improved by a modification of the matrix microstructure through an austempering treatment [2,3]. This thermal treatment comprises austenitization in the temperature range between 850 and 950 °C, followed by quenching in a salt bath furnace at 250–400 °C. The material is then maintained at this temperature for an optimized period to stabilize the austenite, and then it is cooled to room temperature. With this treatment an ausferritic microstructure is produced, characterized by the presence of bainitic ferrite plus carbon stabilized austenite [4,5].

Several investigations were carried out in the last years to study the dry sliding behaviour of austempered cast irons (ADI), in order to favour their use in engineering applications. Many of them were carried out in contact conditions able to produce a delaminative (metallic) form of wear. In these conditions, the surface and subsurface regions are submitted to large plastic shear stresses. Microstructure plays an important role since it is able to strain harden and the retained austenite may transform into martensite [5,6]. In this way the material achieve and increased ability to support the contact load and therefore to contrast wear [7,8]. Perez et al. [9], in particular, highlighted that a Cu–Ni–Mo ADI displayed optimum wear behaviour if treated within a narrow processing window in terms of austempering time and temperature. The importance of a fine ausferrite microstructure for an improved wear resistance was also recently demonstrated by Kumari and Rao [10].

Dry sliding wear may also be controlled by tribo-oxidation. In this case, during sliding the surface asperities or the metallic debris produced in the running-in stage can oxidize, and the oxide particles may agglomerate to form a protective scale [11–13]. Wear is thus typically mild, and it is due to the delamination or fragmentation of the scales [13–15]. The transition from the mild oxidative wear to the severe delamination wear is determined by the working parameters, such as load, sliding speed, temperature and test duration. In general it is induced by the attainment of a critical combination of load and speed at which the formation of the oxide scale is prevented by the material removal by delamination [16,17]. In the case of grey cast irons, Riahi and Alpas [18] produced a comprehensive wear map that displays the load–speed boundary between mild oxidative wear (at the lowest loads and speeds) and the severe delamination wear. In the case of an ADI, Lu and Zhang [7] found that at low loads wear was mild by oxidation and that the subsurface strain induced martensite transformation might increase or reduce the wear resistance. Haseeb et al. [8], on the other hand,

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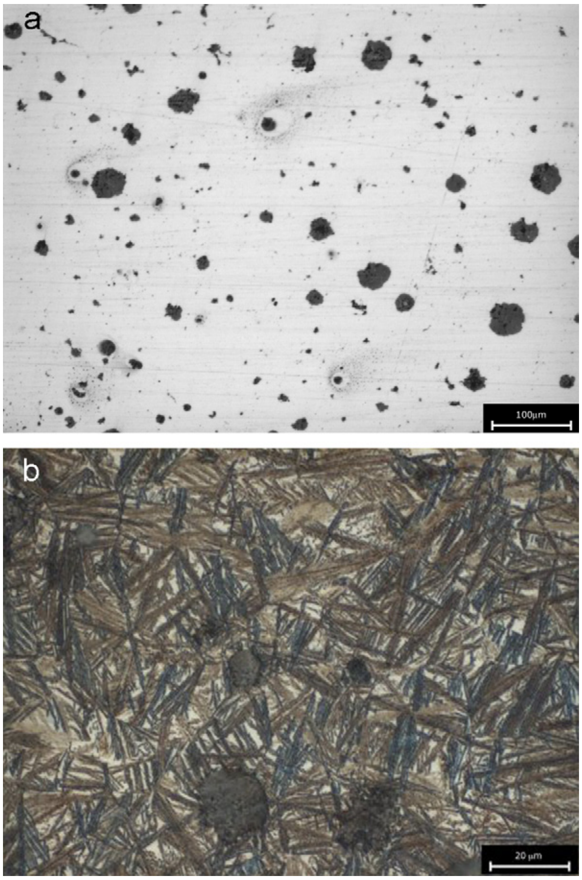


**Fig. 1.** ADI microstructure. (a) Un-etched condition; (b) after etching with 2% Nital.

reported that strain-induced transformation of retained austenite and the strain hardening of bainitic ferrite contributed to the oxidative wear resistance of ADI. In addition, the authors highlighted the superiority of ADI with respect to quenched and tempered nodular cast ions with comparable hardness values. Moreover, Fordyce and Allen [19] showed that the oxidative wear resistance of an ADI increased with sliding speed and with matrix hardness. They also highlighted the formation of patchy and hard white layers on the worn surfaces, but they did not discuss their role in the wear process.

In the present investigation, the dry sliding wear behaviour of an ADI was investigated. The tribological conditions were chosen with the aim of inducing a mechanism of oxidative wear. Attention was focussed on the combined role of sliding speed and applied pressure on the friction and wear behaviour of the ADI, with particular emphasis on the formation of the white layer on the wearing surfaces and its role in the wear process.

## 2. Material and experimental procedures

The ductile iron studied in the present work had the following chemical composition: 3.9% C, 3% Si, 0.4% Mn, 0.1% Cr, 0.1% Ni, 0.05% Cu, 0.02% P and 0.01% S. The materials were austenitized at 930 °C and then austempered at 230 °C for 90 min. These conditions were optimized in a previous work [20]. The ultimate and 0.2% offset yield strength of the material is 999 and 785 MPa, respectively, and the tensile elongation at fracture is 4.45%. The Vickers hardness was determined using a load of 60 kg, and it was found to be 327 HV.

In Fig. 1a the unetched microstructure of the material is shown in order to display the graphite structure. The characteristics of the graphite nodules were determined using an image analyzer connected with the optical microscope. The fraction of graphite was found to be 7.2%, the average nodule count was 195 and the mean nodule diameter was 15 μm.

In Fig. 1b the microstructure of the material after etching with 2% Nital is shown. The matrix is characterized by the typical microstructure of austempered ductile iron, consisting of bainitic ferrite and retained austenite. By means of X-ray diffraction (using Cu-kα radiation) and using the Rietveld method [21], it has been obtained that the amount of retained austenite was 25%.

The dry sliding wear tests were carried out using a pin-on-disc apparatus, at room temperature and at a relative humidity between 30 and 35%. The pins, with a diameter of 6 mm, were made by ADI and the counterface disc was made by a pearlitic cast iron with a hardness of 450 HV 60. The sliding surfaces had an initial roughness of $R_a = 0.5$ μm. The sliding speed ranged between 0.2 and 2.6 m/s. Two nominal applied pressures were investigated: 1.1 and 1.5 MPa. The sliding distance was 7 km. The weight loss was determined as a function of sliding distance to a precision of 0.1 mg. The obtained values were converted into wear volumes by considering a density of 7.4 g/cm$^3$. At least three tests for each experimental point were carried out.

During each test, the evolution of the friction coefficient and of the pin temperature was also recorded. For the temperature measurements, a chromel-alumel-type thermocouple was placed in a hole (with a diameter of 0.8 mm) at a distance of 8 mm from the sliding surface. The average surface temperature was then obtained by considering a linear heat flow and using the approach developed by Ashby et al. [22] and Zhang and Alpas [23].

Information on the wear mechanisms was obtained by examining the worn traces and the subsurface damaged zones by optical microscopy. The surface and subsurface layer were also analysed by means of microhardness profiles using a Vickers indenter and a load of 50 g.

## 3. Results

After a short running-in stage (less then 400 m), wear loss was observed to increase almost linearly with sliding distance. In Fig. 2a the experimental steady-state wear rates are then reported as a function of the sliding speed. In agreement with [19], wear rates are found to decrease with sliding speed. However, the applied pressure displays a particular role. If the sliding speed is low, i.e. lower than 1 m/s, wear rate decreases with the applied pressure. If the sliding speed is high, i.e. greater than 1.5 m/s, the opposite trend is observed. The specific wear rates, given by the ratio of the wear rate and the applied load, vary between $10^{-15}$ and $10^{-14}$ m$^2$/N. These values are typical of a mild oxidative wear [12,16].

In Fig. 2b the steady-state friction coefficients are reported as a function of the sliding speed (in the case of friction, steady-state was reached later, after about 3500 m of sliding). Friction coefficient is seen to decrease with sliding speed. Also in this case the role of the applied pressure is different at high or low sliding speeds. It can be therefore state that a transition in the friction and wear behaviour is observed in passing from low sliding speeds (0.5 and 1 m/s) to high sliding speeds (1.5, 1.9 and 2.6 m/s).

In Fig. 2c the recorded contact temperatures are displayed as a function of the sliding speed. Similarly to friction coefficient, the steady-state values are reached after a sliding distance of about 3500 m. It can be noted that surface temperature increase with sliding speed although friction coefficient decreases. This means that sliding speed plays an overwhelming role in local heating and thus in the determination of the surface temperature. As expected, surface temperature is also shown to increase with contact pressure. No transition is observed in passing from low to high sliding speeds.