

Influence of shot peening on the rolling contact fatigue resistance of Cu-Ni austempered ductile iron

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Abstract

Shot peening is known to prolong the bending fatigue life of components. However, very few works have been conducted on the tribological behaviour of ADI after shot peening. This paper studies the influence of shot peening on the contact fatigue resistance of Cu-Ni ADI. Lubricated rolling contact fatigue tests were conducted on as-austempered ADI and shot peened ADI specimens. The results show that the shot peened specimens exhibit lower rolling contact fatigue resistance than their counterpart as-austempered specimens. This was attributed to the high surface roughness induced by the shot peening process, which caused a boundary lubrication regime. In fact, the negative impact resulting from the roughened surface is greater than the benefits prompted by the induced compressive residual stresses, higher surface hardness and austenite to martensite transformation.

Keywords

Shot peening, rolling contact fatigue, austempered ductile iron, lubrication regime

Introduction

Austempered ductile iron (ADI) offers numerous positive advantages including: good combination of mechanical properties, good damping characteristics, lower density than steel and the possibility of casting components into near-net shape. However, surface engineering techniques are necessary to extend its use and application in industry.

Shot peening is one such treatment which induces high residual compressive stresses and high dislocation densities at the surface of components [1]. This suppresses cracking and delays crack growth, which in turn, prolongs the lifetime of components, and should be beneficial in reducing wear rates. In addition, the dimples resulting from shot peening can act as reservoirs that aid in retaining the lubricant [2, 3]. That said, Vaxevanidis et al. [4] still reported improved sliding wear resistance of shot peened steel tested under dry conditions. Even under boundary lubrication, Adamović et al. [5] reported over 35% increase in the wear resistance of steel after shot peening. In contrast, lubricated rolling contact fatigue tests carried out by Ohba et al. [6] showed that shot peened Cu-alloyed ADI exhibited similar wear rates to corresponding as-austempered specimens. This was attributed to surface roughening which counterbalances the positive effects of compressive stresses and hardening caused by shot peening. Work by Sharma [7] showed that the contact fatigue life of Mo-Ni ADI is 35–45% lower than that of carburised steel. The author attributed this to the rougher surface and a lower hardness of the shot peened ADI when compared to carburised steel. The above shows that it is not clear whether shot peening actually improves the tribological characteristics. Additionally, very few works have been conducted to study the tribological behaviour of ADI after shot peening. This paper compares the rolling contact fatigue resistance of as-austempered ADI to that of corresponding shot peened ADI specimens under lubricated conditions.

Experimental Procedure

Material and processing

The resistance to contact fatigue of as-austempered ADI and shot peened ADI was tested using a cone-three ball tribosystem. This test consists of an upper driven ADI cone which is brought into loaded contact with three lower 100Cr6 steel balls, which are polished to a mirror

finish. The cones used in the fatigue tests were machined from ductile iron keel blocks having the composition shown in

Table 1. After machining, the samples were austenitised at $900 \pm 3^\circ\text{C}$ for two hours and austempered in a salt bath held at $360 \pm 5^\circ\text{C}$ for one hour. These austempering parameters were optimised in a previous study by the same authors [8].

Table 1 – Chemical composition of the ductile iron keel blocks

Element	C	Si	Cu	Ni	Mn	P	Mg	Al	S	Fe
wt%	3.26	2.36	1.63	1.58	0.24	0.011	0.057	0.024	0.006	Bal.

Surface treatment

After heat treatment, the ADI cones were manually ground and polished up to a mean surface roughness R_a of $0.05 \mu\text{m}$. Half of the cones were subsequently shot peened. Shot peening was carried out using S330 shots, with an Almen intensity of 0.38 mmA up to 100% coverage. The stand-off distance was 90 mm, while the angle of impingement was set at 90° . The surface roughness R_a of the shot peened cones was measured to be $3.12 \mu\text{m}$.

Test equipment and conditions

The contact fatigue tests were carried out using the T-03 modified four-ball pitting tester [9]. In these tests, the lower balls are allowed to rotate freely in a race filled with lubricating oil, simulating pure rolling conditions. This test follows the IP 300 standard [10], where a number of runs are carried out for each surface condition, and the time to pitting is recorded for each run. All the tests were carried out using an applied load of 294 N, corresponding to an applied stress of 2.56 GPa, a rotational speed of 1450 rpm, and 75W-90 gear oil as the lubricant. The tests were performed at an ambient temperature of $22 \pm 3^\circ\text{C}$ and relative humidity of $42 \pm 4\%$. At least fifteen tests were carried out for each of the two surface conditions: polished as-austempered ADI and shot peened ADI. New cones and balls were used for each test. The contact fatigue life of each surface condition was determined by using the Weibull analysis method [11]. The duration of the tests were converted into number of cycles on the cone by using a stress cycle factor of 2.4.

Characterisation

The mean surface roughness measurements for the as-austempered and shot peened specimens were conducted using a Taylor Hobson TALYSURF CCI non-contact optical interferometer. The 3D images of the pits were obtained using Taylor Hobson Form Talysurf contact profilometer. The microhardness measurements were taken using a Mitutoyo MVK-H12 testing machine. The reported results for hardness and roughness are the average values of at least three measurements. A 95% confidence level was applied in all cases.

Results and discussion

Characterisation of microstructures

The microstructure of the as-austempered material contains 200 graphite nodules per mm^2 and a graphite nodularity greater than 95% in a matrix consisting of acicular ferrite and carbon enriched austenite. The microhardness of the ausferritic structure is $370 \pm 10 \text{ HV}$. Following shot peening, the 40% retained austenite present in the as-austempered structure transformed to martensite. This was presented in other publications by the same authors [12, 13]. The work hardening induced by shot peening and the phase transformation to martensite resulted in an increase in the surface hardness from 370 to 535 HV. The maximum residual stresses present in the shot peened specimens was shown to occur at the surface and had a value of about 975 MPa [12].

Contact fatigue resistance of ADI

Fig. 10a presents the results obtained on a Weibull probability plot, while Fig. 10b shows the L_{10} , L_{50} and characteristic (η) fatigue lives. These represent the number of cycles following which 10%, 50% and 63.2% of a large number of cones are expected to fail.

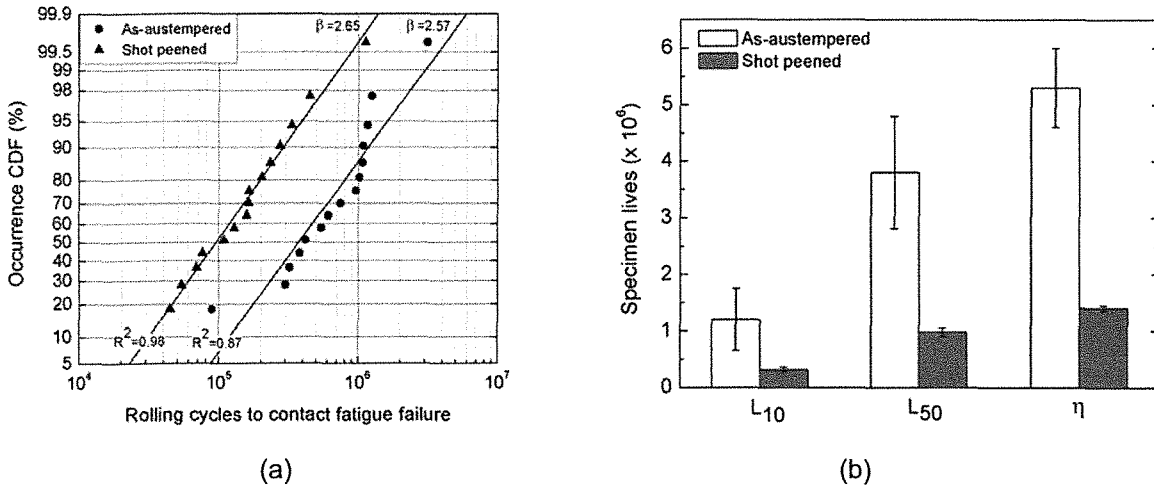


Fig. 10 – (a) Weibull probability plot for data obtained from rolling contact fatigue tests; (b) L_{10} , L_{50} , characteristic (η) fatigue lives for as-austempered and shot peened ADI specimens

The L_{10} , L_{50} and characteristic lives for the polished as-austempered ADI specimens are respectively 1.2×10^5 , 3.8×10^5 and 5.3×10^5 cycles. These values are of the same order as results obtained by Xu and Lu [14] where ADI specimens austempered at 370°C and loaded at a stress of 2.3 GPa survived 2×10^5 cycles. A higher number of cycles to failure were obtained by Dommarco et al. [15], who report values of 3.5×10^6 , 9.3×10^6 and 11.2×10^6 cycles respectively for the L_{10} , L_{50} and characteristic lives. This can be attributed to the lower applied contact stress of 1.6 GPa, when compared to the 2.6 GPa applied in the current study.

When comparing the performance of the shot peened specimens to that of as-austempered the specimens, results show that shot peening decreased the contact fatigue characteristic fatigue life (η) by 3.9×10^5 cycles. Lower contact fatigue lives after shot peening were also reported in other studies carried out on ADI [7] and steel specimens [16].

In the current study, austempering at 360°C resulted in a hardness of 370 HV, while shot peening increased the surface hardness to approximately 530 HV. Based solely on the increase in hardness, improvement in the contact fatigue resistance is expected. In addition, the residual compressive stresses induced in the surface, should serve to reduce the maximum shear stress inside the Hertzian contact field, and to delay crack nucleation and propagation. However, the surfaces of the shot peened specimens have a higher surface roughness ($R_a = 3.12 \mu\text{m}$) than the counterpart as-austempered specimens ($R_a = 0.05 \mu\text{m}$). This leads to an extremely low value of the specific film thickness, λ , of 0.05 for the shot peened specimens. A value of λ smaller than 0.4 denotes that a boundary lubricated condition exists, signifying that the peaks of the asperities of the shot peened specimens penetrate the lubricant film. As a result of the lower value of λ , contact occurs between the cone and balls. This implies that nearly the total load is being supported by the asperities. This defies the principal purpose of applying lubrication. Consequently, failure by contact fatigue starts from the surface as a result of the presumably high coefficient of friction.

In contrast, the smooth surfaces of the as-austempered specimens result in a relatively high value of the specific film thickness, λ , of 2.81. Values of λ greater than 1 indicate the presence of a full lubricant film separating the surfaces. This leads to elastohydrodynamic lubrication (EHL) conditions, which are ideal during the operation of a component under rolling contact

[17]. However, the existence of EHL oil film does not eliminate the cyclic stressing of the surfaces, but only lessens it. In fact, after a number of cycles, the specimens still fail by contact fatigue, where prolonged contact results in pitting, as shown in Fig. 11a.

In case of rough shot peened surfaces, the minimum oil thickness providing full lubrication should be higher than the combined surface roughness of the interacting surfaces. Researchers choose various ways to obtain such conditions. Ohba et al. [6] used small 0.1 mm diameter shots and reported the fatigue life of shot peened ADI to be nearly equal to ground as-austempered ADI. Vrbka et al. [16] found that the rolling contact fatigue resistance decreased using shots having 0.07–0.11 mm diameter, but obtained a fatigue life improvement when applying the polishing process to the shot peened specimens. However, processes such as grinding or polishing might be challenging since the risk of removal of the shot peened layer eliminates the positive effects which of shot peening.

Specimen analysis following rolling contact fatigue testing

Several small pits were observed on the wear track of the shot peened specimens as shown in Fig. 11c. In contrast, solitary pits were seen on the as-austempered samples (Fig. 11a). The 3D images of the pits presented in Fig. 11b and d also show that the pits on the shot peened specimens were smaller and shallower than those on the as-austempered specimens. This is due to the resulting surface initiated cracks in shot peened specimens which results in pits that are usually shallower than those initiated from sub-surface defects [18]. On the other hand, the presence of a full oil film between the rolling specimens and the absence of surface shear in the polished as-austempered specimens, results in sub-surface crack initiation. This is the dominant mode of failure in rolling elements having smooth surfaces and which operate under EHL conditions [18]. Sub-surface cracks initiate from material imperfections situated close the plane of maximum shear stress within the Hertzian contact, which was calculated to occur at a depth of around 70 μm . Material imperfections include non-metallic inclusions, micro-shrinkage pores, or even irregularly shaped graphite at or near the surface.

In addition to pitting, micropitting and grey staining was sometimes observed on the wear track or around the pits, as shown in Fig. 12a. This also occurs as a result of contact fatigue, and would probably have led to further pitting if the test was not stopped soon after pitting was initiated. Apart from the occurrence of pits, delamination of the surface was noted on the wear tracks as shown in Fig. 12b.

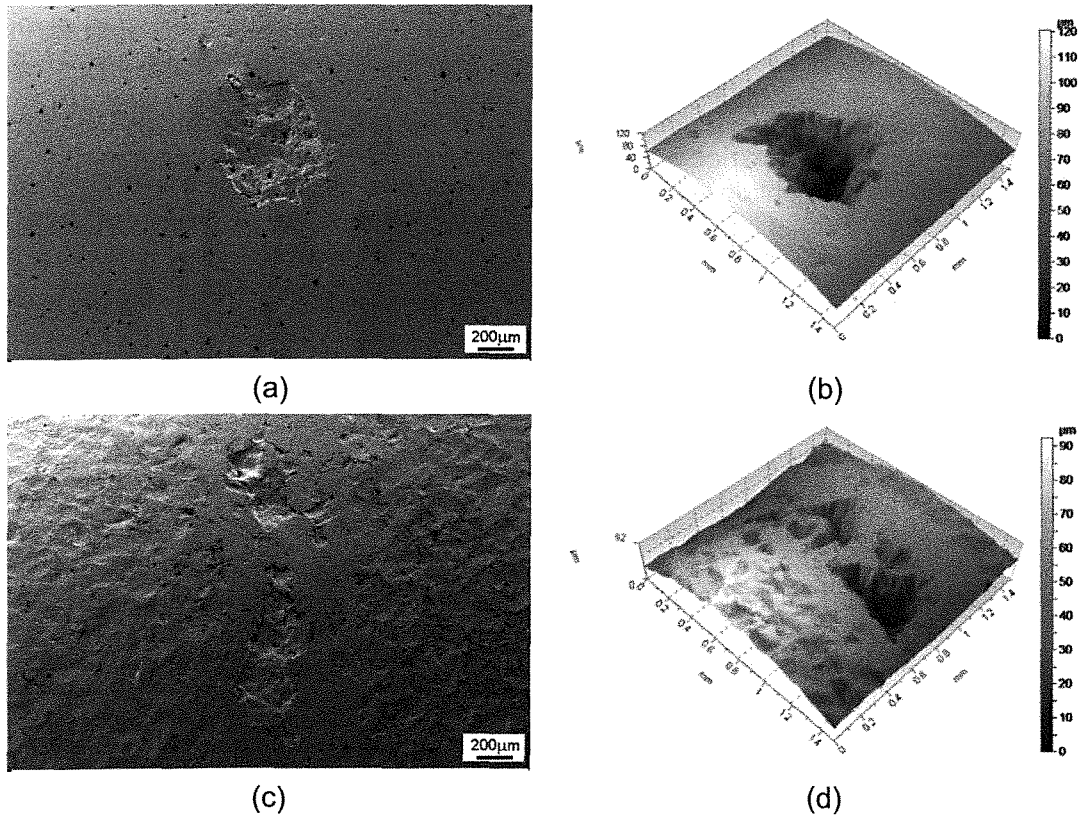


Fig. 11 - SEM images and corresponding 3D images for contact fatigue pits on (a-b) as-austempered and (c-d) shot peened specimens.

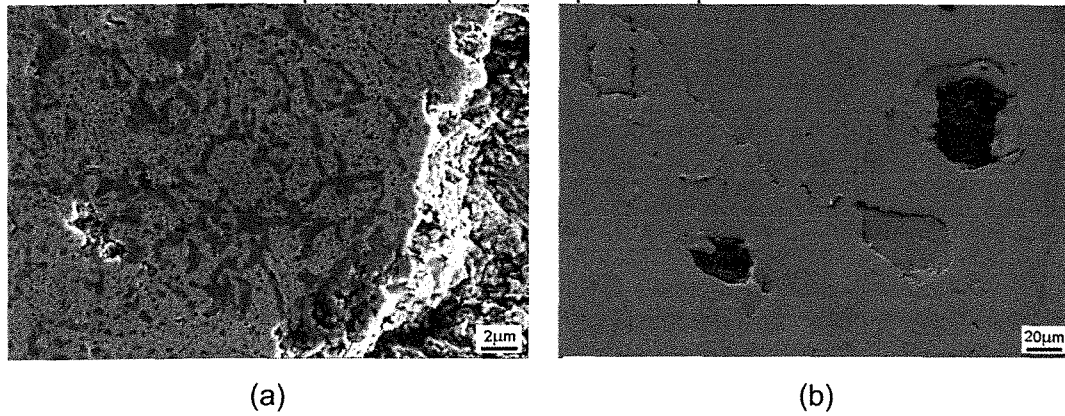


Fig. 12 – SEM images showing (a) micropitting and grey staining and (b) cracks and delamination on the wear track surfaces

Conclusions

This study was carried out so as to determine the influence of shot peening on the rolling contact fatigue resistance of a Cu-Ni austempered ductile iron. The results were compared to contact fatigue lives exhibited by as-austempered ADI specimens. Results showed that shot peening decreased the rolling contact characteristic fatigue life by 3.9×10^5 cycles. This was attributed to the rough surfaces which in turn caused a low specific film thickness, leading to rolling in the boundary lubrication regime. In contrast, the polished as-austempered specimens were tested in the presence of a full lubricant film which separates the surfaces, hence resulting in longer fatigue lives. This study has shown that shot peening using S330 shots and an intensity of 0.38 mmA is not beneficial in increasing the rolling contact fatigue life of austempered ductile iron.

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