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ROLLING CONTACT FATIGUE RESISTANCE OF SHOT PEENED AUSTEMPERED DUCTILE IRON

ODPORNOŚĆ NA POWIERZCHNIOWE ZUŻYCIE ZMĘCZENIOWE ŻELIWA ADI PODDANEGO KULOWANIU

Key words:

rolling contact fatigue resistance, shot peening, austempered ductile iron

Słowa kluczowe:

powierzchniowe zużycie zmęczeniowe, śrutowanie, żeliwo ADI

Abstract

Compared to other ferrous materials, austempered ductile iron (ADI) has marked economic advantages such as low melting temperature, low shrinkage, excellent castability, good machinability, and high damping capacity. This makes it a potential candidate material for automotive components. The desired

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bulk properties required by these components can be obtained through careful control of the austempering parameters. However, to truly unlock its full potential, surface engineering techniques are necessary to improve the surface properties and characteristics of this material. This study provides an insight on the tribological behaviour of shot peened ADI. Lubricated rolling contact fatigue tests revealed that shot peening resulted in a 72% decrease in the average contact fatigue life when compared to the resulting fatigue life obtained by the as-austempered ADI specimens.

INTRODUCTION

The high hardness due to work hardening and stress-induced austenite to martensite transformation on the surface of shot peened specimens should be beneficial in reducing wear rates **[L. 1–3]**. Additionally, residual compressive stresses should suppress crack formation and delay of crack growth. Kobayashi and Hasegawa **[L. 4]** showed this to be true for carburised steel gears.

Champaigne **[L. 3]**, as well as Townsend and Zaretsky **[L. 5]**, reported an improvement in the contact fatigue life of shot peened steel gears of around 1.5 times. In another study, Townsend [6**]** reported that a higher intensity (0.38–0.43 mmA) resulted in higher compressive stresses, and hence lead to a 10-percent rolling contact fatigue life (L_{10}) of 2.15 times that of the carburised gears peened with an intensity of 0.18–0.23 mmA.

Studies on the rolling contact fatigue resistance of austempered ductile iron (ADI) are scarce. Rolling contact fatigue tests carried out by Ohba et al. **[L. 7]** showed that shot peened ADI alloyed with 0.73% Cu and austempered at 310°C exhibit similar wear rates as corresponding peened and ground specimens tested under point contact conditions. The reason given is that surface roughening counterbalances the positive effects of compressive stresses and hardening caused by shot peening. On the other hand, work by Sharma **[L. 8]** showed that at a given load, the contact fatigue life of shot peened Mo-Ni ADI austempered at 230°C 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.

Such studies show that there is still uncertainty as to whether shot peening actually improves the tribological characteristics. 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

The contact fatigue tests were carried out using a cone-three ball tribosystem as shown in **Fig. 1**. The equipment used was the T-03 modified four-ball pitting tester **[L. 9]**, and tests followed the IP 300 standard **[L. 10]**. This test consists of an upper driven ADI cone that is brought into loaded contact with three lower 100Cr6 steel balls, which are polished to an R_a value of 0.032 μm. The lower balls are allowed to rotate freely in a race filled with lubricating oil, simulating pure rolling conditions. The cones used in the fatigue tests were machined from ductile iron keel blocks having the following composition: 3.26% C, 2.36% Si, 1.63% Cu, 1.58% Ni, and 0.24% Mn. After machining, the samples were austenitised at 900°C for two hours and austempered in a salt bath held at 360°C for one hour. These austempering parameters were optimised in a previous study by the same authors **[L. 11]**.

All the tests were carried out using an applied stress of 2.56 GPa, a rotational speed of 1450 rpm, and Shell Transaxle 75W-90 gear oil as the lubricant. The tests were performed at an ambient temperature of 22±3°C and a relative humidity of 42±4%. Fifteen tests were carried out for each of two surface conditions: polished as-austempered ADI and shot peened ADI, respectively, having R_a values of 0.05 μm and 3.12 μm. New cones and balls were used for each test. 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°. These parameters were optimised in another study by the same authors **[L. 12]**.

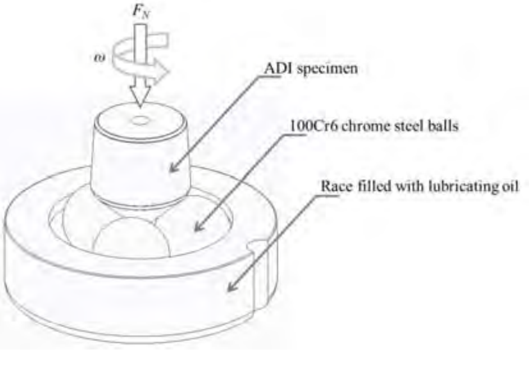


Fig. 1. The cone-three ball tribosystem used in the rolling contact fatigue tests
Rys. 1. Skojarzenie stożek–trzy kule stosowane w badaniach powierzchniowego zużycia zmęczeniowego

The duration of the tests, which is the time until the onset of pitting, was converted into the number of cycles on the cone by using a stress cycle factor of 2.4. The results presented are the average contact fatigue life of each surface condition. Hypothesis testing was carried out in order to identify the statistical difference between the means of the populations of the two surface conditions. A two-tailed unpaired *t*-test with a 95% confidence level and a level of significance of 0.025 was used. In the reported results, μ_x is the mean value while *s* is the standard deviation of the sample.

The induced residual stresses after shot peening were determined by means of the incremental hole drilling method by which an oscillating drill (Ø 1.9 mm) is driven by an air-turbine providing a rotational speed of 200,000 rpm. From the back strains measured by strain gauge rosettes, the residual stresses were calculated using linear elasticity concepts. The results are an average of two measurements. The mean surface roughness measurements and 3D images of the surfaces of the as-austempered and shot peened specimens were conducted using a Taylor Hobson TALYSURF CCI non-contact optical interferometer. The pit profiles were obtained using a 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

Material characterisation

Following austempering, the resultant microstructure consisted of graphite nodules dispersed in a matrix of ferrite and high carbon retained austenite. This is presented in the micrograph shown in **Figure 2.** This microstructure has a nodule count of 200 graphite nodules per mm^2 and graphite nodularity greater than 95%.

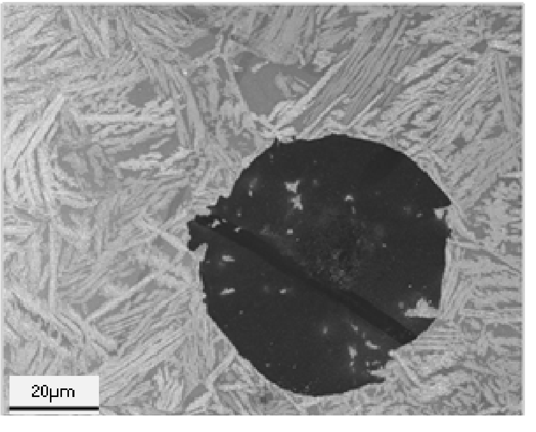
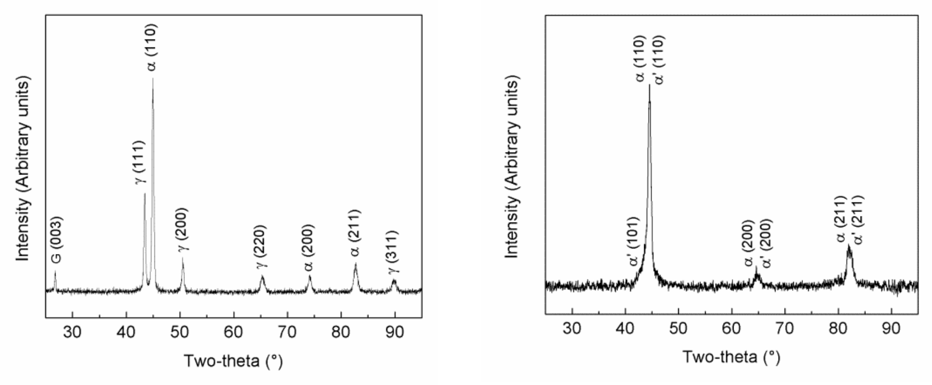


Fig. 2. ADI microstructure; etched with 2% nital
Rys. 2. Mikrostruktura żeliwa ADI, trawienie w 2% roztworze nitalu

The austenite peaks present in the XRD pattern for the as-austempered ADI structure (**Figure 3a**) are not visible in the pattern for the shot peened ADI structure (**Figure 3b**). Instead, peak broadening is present at a two-theta value of around 44°, which is due to superimposition of the (1 0 1) and (1 1 0) martensite doublets, and the (1 1 0) ferrite peak **[L. 13]**. This shows that, following shot peening, the retained austenite was transformed to martensite. As a result of this phase transformation and the induced work hardening by shot peening, the microhardness at the surface increased from 370±10 HV to 535±6 HV. Additionally, shot peening induced residual compressive stresses, having a value of 975±90 MPa in the surface of the ADI. The residual stress-depth profile is shown in **Figure 4**. These stresses are due to cold working by shot peening and because of the 4% increase in volume when the fcc austenite transforms to bct martensite. This leads to the creation of further sub-microscopic stresses and dislocations.



(a) (b)

Fig. 3. XRD patterns for (a) as-austempered ADI and (b) shot peened ADI
Rys. 3. Widma XRD dla: a) żeliwa ADI w stanie wyjściowym, b) tegoż żeliwa po kulowaniu

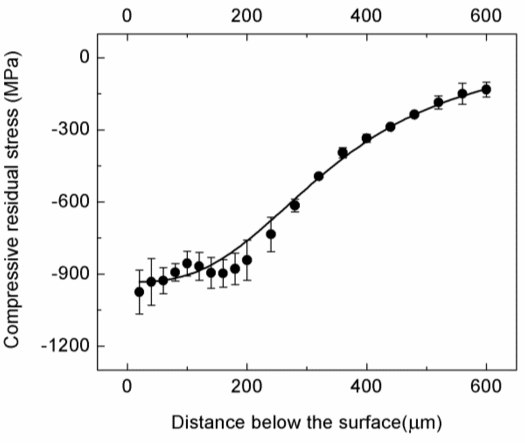


Fig. 4. Residual stress-depth profile
Rys. 4. Rozkład naprężeń własnych w funkcji głębokości

Contact fatigue performance

Figure 5 shows the average contact fatigue lives for the as-austempered ADI and shot peened ADI specimens. Results show that the average contact fatigue life of shot peened specimens (μ_x = 2.4×10^5, s = 2.7 ×10^5) decreased by 72% when compared to the performance of the as-austempered specimens (μ_x = 8.7 × 10^5, s = 7.2 ×10^5), t(28) = -3.19. The 72% decrease has an effect size r of 0.52 signifying a large effect **[L. 14]**.

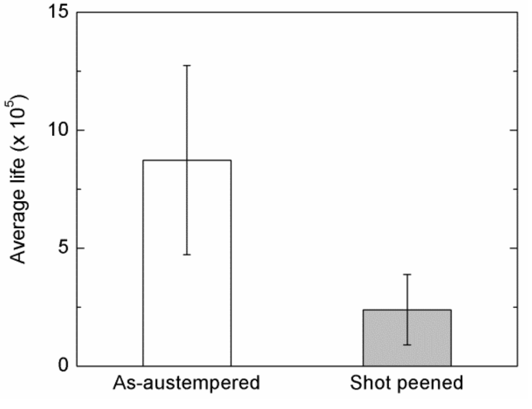


Fig. 5. Average life for the as-austempered ADI and shot peened ADI specimens
Rys. 5. Średnia trwałość dla żeliwa ADI w stanie wyjściowym i po kulowaniu

Similarly, Sharma et al. **[L. 8]** reported that shot peening lowered the contact fatigue life of ADI by 60%. Also, Vrbka et al. **[L. 15]** report an 82% decrease in life of steel specimens following rolling contact fatigue tests.

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 only on hardness, one would expect an improvement in the contact fatigue resistance. In addition, the residual compressive stresses present in the shot peened layers should effectively reduce the maximum shear stress inside the Hertzian contact field, delaying crack nucleation and propagation.

However, as shown in **Figure 6**, the surfaces of the shot peened specimens have a higher surface roughness (R_a = 3.12 μm) than their counterpart as-austempered specimens (R_a = 0.05 μm). The former leads to an extremely low value of the specific film thickness λ of 0.05, which contrasts to a corresponding value of 2.81 for the as-austempered specimens. A value of λ smaller than 0.4 denotes that a boundary lubricated condition exists, implying that peaks of the asperities of the shot peened specimens are penetrating the lubricant film. Therefore, contact occurs between the asperities of the shot peened ADI cones and balls. Metal-to-metal contact is unavoidable and nearly all the load is supported by the asperities, defying the principal purpose of lubrication. Failure by contact fatigue starts from the surface because of a presumably high coefficient of friction.

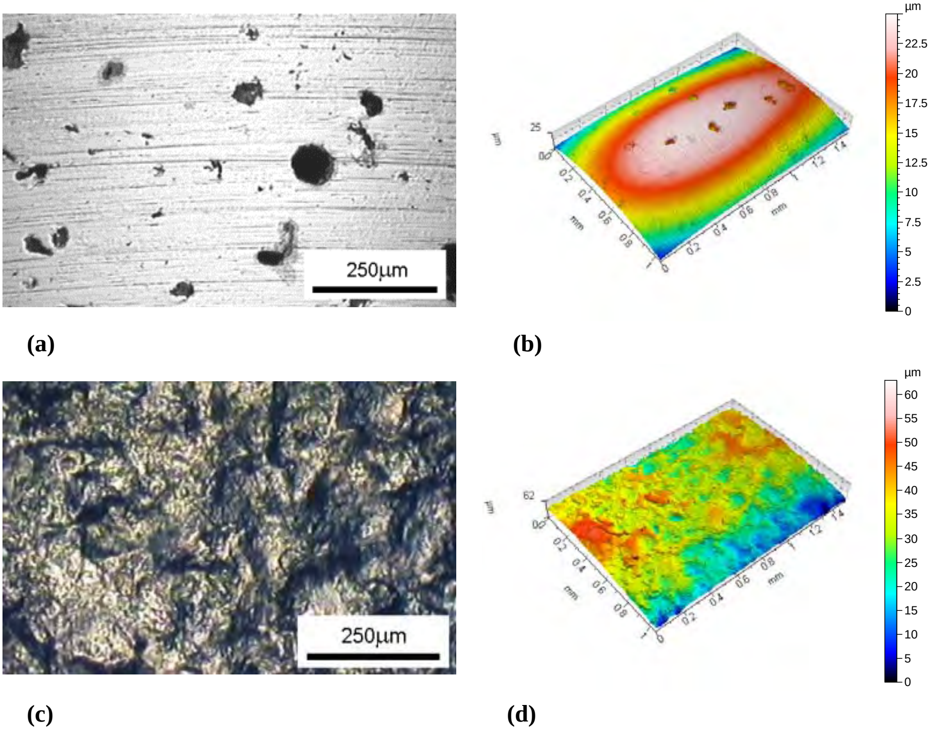


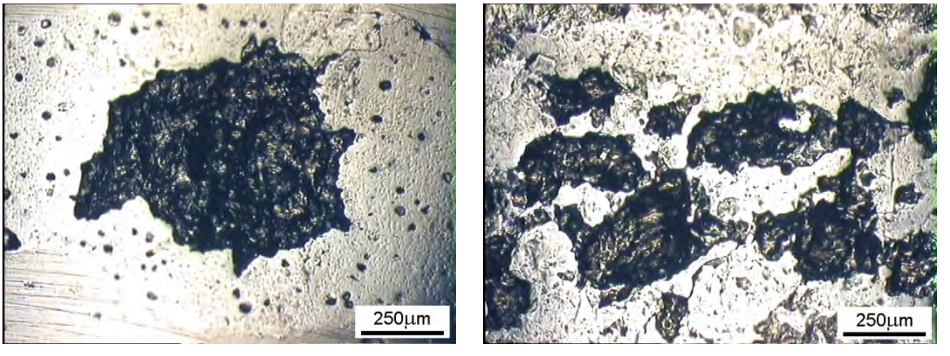
Fig. 6. Optical micrographs and 3D images of surfaces before contact fatigue tests for (a-b) as-austempered ADI and (c-d) shot peened ADI specimens; unetched

Rys. 6. Obrazy optyczne i profile 3D z powierzchni tarcia: a, b) żeliwo ADI w stanie wyjściowym, c, d) żeliwo ADI po kulowaniu (bez trawienia)

It could also be the case that, during shot peening, the graphite nodules are removed from the surface because of the shot impacts on the surface. This creates a number of defects on the surface, which act as sources of crack nucleation leading to premature failure.

As shown in **Figure 7b**, several small pits were observed on the wear track of the shot peened specimens. In contrast, solitary pits were seen on the as-austempered samples (**Figure 7a**). The pits observed in all the specimens were 50 to 100 µm deep. According to Ding and Rieger **[L. 16]**, pits which are 20–100 µm deep can be classified as spalls. **Figure 8a** and b also show that the pits on the shot peened specimens were smaller and less deep than the as-austempered specimens. This is due to the fact that pits initiated from surface defects are usually shallower than those initiated from sub-surface defects **[L. 16–18]**. On the other hand, the absence of surface shear in the polished as-austempered specimens was due to the full oil film between the rolling specimens that favoured sub-surface crack initiation. This is the dominant mode of failure in rolling elements having smooth surfaces and which operate under EHL conditions **[L. 17]**.

Sub-surface initiated pitting is caused by the Hertzian stress, which is the maximum shear stress acting below the surface. This was calculated to have a value of 0.82 GPa and occurs at a depth of around 70 μm. Sub-surface cracks initiate from material imperfections situated close to the plane of maximum shear stress within the Hertzian contact. Imperfections include non-metallic inclusions, micro-shrinkage pores, or even irregularly shaped graphite at or near the surface.



(a) **(b)**

Fig. 7. OM images showing the pits present after failure of: (a) as-austempered ADI and (b) shot peened ADI specimens; unetched

Rys. 7. Obrazy optyczne uszkodzenia pittingowego: a) żeliwo ADI w stanie wyjściowym, b) żeliwo ADI po kulowaniu (bez trawienia)

Once a crack is nucleated, high stress concentrations are created around the crack tip, which favours crack propagation. It is believed that, when a crack is formed, it reaches the surface after repeated load cycles. The pressure caused by the lubricant penetrating the specimen through these cracks leads to their opening and growth and, as a consequence, a piece of the material breaks off causing a volume of metal to be lost from the surface, resulting in surface pitting **[L. 19, 20]**. In addition to pitting, micropitting, and grey staining were at times observed on the wear track or around the pits, as shown in **Figure 9**. This is also as a result of contact fatigue and may change the surface topography of the component during rolling **[L. 21]**. This micropitting would probably have led to more severe pitting had the test not been stopped soon after pitting was initiated. The onset of pitting was characterised by an increase in the noise emitted by the tribo-system, which was caused an increase in the vibrations. The debris formed when pitting starts can cause gouging, scratching and denting of the surface, creating new sites for crack development and leading to further pitting and an increase in the vibration.

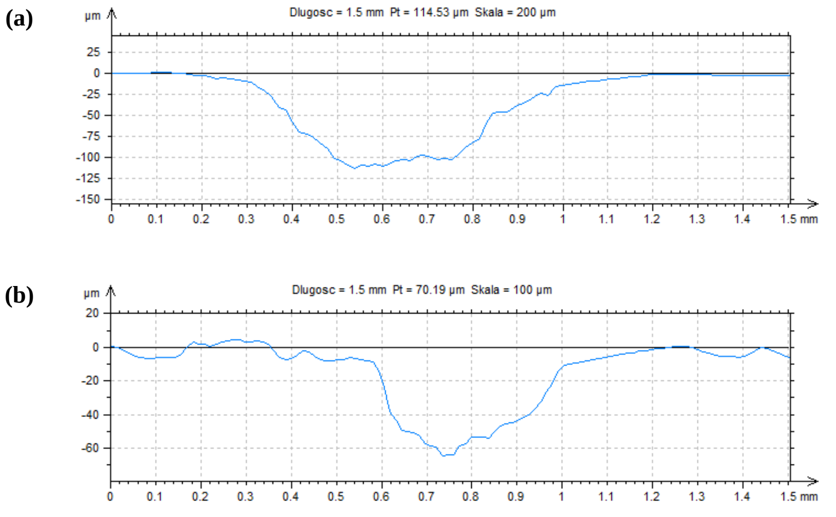


Fig. 8. Typical pit profiles for: (a) as-austempered ADI and (b) shot peened ADI specimens
Rys. 8. Profile w poprzek uszkodzenia pittingowego: a) żeliwo ADI w stanie wyjściowym, b) żeliwo ADI po kulowaniu

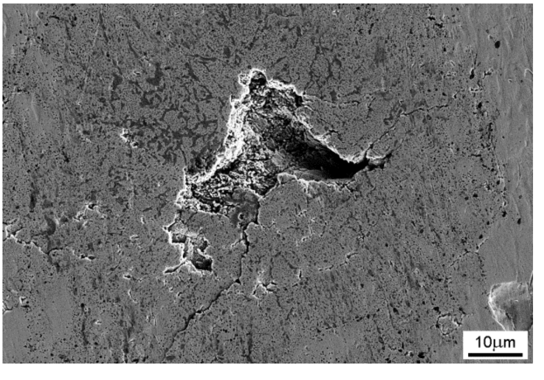


Fig. 9. A pit surrounded by micropitting and grey staining observed on the wear track; unetched
Rys. 9. Uszkodzenie pittingowe wraz z otaczającym je obszarem z mikropittingiem ma śladzie tarcia (bez trawienia)

CONCLUSIONS

This study was carried out in order to determine the influence of shot peening on the rolling contact fatigue resistance of the austempered ductile iron under investigation. Results showed that the rolling contact fatigue life decreased by 72% as a result of shot peening. This was attributed to rolling being conducted in the boundary lubrication regime because of the rough shot peened surfaces. This high surface roughness led to a low specific thickness resulting in the surface asperities breaking through the oil film between the mating surfaces. In contrast, the smoother surfaces of the polished as-austempered specimens led to testing being carried out in the presence of a full elastohydrodynamic film.

Analysis of the specimens following contact fatigue testing revealed that failure of the as-austempered ADI specimens was initiated from defects present at the sub-surface. This resulted in deeper pits than those observed in the specimens that were shot peened. This was due to the failure of the shot peened specimens commencing from the surface because of the interaction of surface asperities during testing.

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Streszczenie

W porównaniu ze stalą i staliwem żeliwo ADI cechuje się korzystniejszymi cechami użytkowymi, takimi jak niska temperatura topnienia, niewielki skurcz odlewniczy, doskonała lejność, dobra obrabialność i wysoka zdolność do tłumienia drgań. Cechy te czynią żeliwo ADI potencjalnym materiałem do zastosowania w przemyśle motoryzacyjnym. Parametry materiałowe wymagane dla tych elementów maszyn mogą być uzyskane jedynie w wyniku prawidłowego przeprowadzenia procesów obróbki cieplnej skutkujących wytworzeniem struktury ausferrytycznej. Jednakże, by żeliwo to mogło być stosowane, niezbędna jest także poprawa właściwości użytkowych warstwy wierzchniej. W artykule zaprezentowano wyniki badań tribologicznych śrutowanego żeliwa ADI. Testy powierzchniowego zużycia zmęczeniowego wskazały na zmniejszenie o 72%, średniej trwałości żeliwa ADI po kulowaniu w stosunku do tegoż żeliwa w stanie wyjściowym.