Bending Fatigue Resistance of Duplex Shot Peened Austempered Ductile Iron

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Abstract

This study investigates conventional and duplex shot peening as a means to further improve the fatigue behaviour of austempered ductile iron. This involves characterisation of surface regions through microstructural analysis, phase analysis, and synchrotron radiation stress measurement, amongst other techniques. Additionally, rotating bending fatigue testing revealed that both shot peening variants enhanced the fatigue strength of ADI by 65%. Moreover, duplex shot peening brought about an improvement in fatigue life relative to conventionally shot peened specimens. This was attributed to a reduction in surface roughness of approximately 30% along with amplified magnitudes of compressive residual stresses.

Keywords Austempered ductile iron, duplex shot peening, fatigue strength, fractography, strain induced transformation.

Introduction

Austempered ductile iron (ADI) has a remarkable combination of mechanical properties and tribological characteristics, such as high tensile and fatigue strength, good wear and rolling-contact fatigue resistance, and appreciable ductility [1, 2]. The potential of ADI as a viable material in the automotive industry may be further enhanced through shot peening (SP). The residual compressive stresses, together with the increased dislocation density and the strain induced transformation of austenite into martensite at the surface, significantly improve the fatigue life of the peened components along with the hardness of the surface layer. Zammit et al. [3] investigated the effect of shot peening on Cu-Ni ADI, observing that the fatigue strength was increased by 60%. Similarly, Benam et al. [1] observed improvements ranging from 27% to 50% for Cu-Ni ADI austempered at temperatures ranging from 320℃ to 400℃ respectively. The former study [3] also reported consistent improvements in fatigue life of approximately 35% at all stress levels, with peak stresses of around 560 MPa. On the other hand, Benam et al. [1] observed that improvements in fatigue life were much less pronounced at stress levels exceeding 500 MPa. Overall, several studies corroborate the positive impact of shot peening on fatigue performance, results ranging from an improvement of 23% [4] to 115% [5], with other authors reporting values falling anywhere within the range. A variant of the conventional shot peening process is duplex shot peening, which employs a secondary peening operation, typically using smaller shots and a lower peening intensity [6]. While this mechanical surface engineering treatment has never been applied to ADI, promising results have been reported for other ferrous materials, such as medium carbon steel [7] and duplex stainless steel [8].

To investigate the potential of shot peening and duplex shot peening of ADI, this study employs a holistic approach involving the characterisation of as-treated and shot peened ADI specimens. This allowed for the analysis of various aspects, such as compositional and microstructural changes, brought about by the heat treatment and surface engineering techniques implemented in this study. The accompanying improvements in mechanical properties, specifically the fatigue behaviour of ADI, are evaluated through rotating bending fatigue testing at different applied stress levels.

Experimental Methods

Hourglass-type specimens, having dimensions shown in Figure 1, were machined from standard Y-shaped ductile iron keel blocks. The as-cast material had a nodule count of 213.6/mm^2 and a nodularity exceeding 85%. The main elements making up the ductile iron are 90.7 wt% Fe, 3.3 wt% C, 2.4 wt% Si, 1.7 wt% Cu, 1.6 wt% Ni. The specimens were first austenitised in an electric furnace at 900°C for 120 minutes, then austempered in a salt bath at 360°C for 90 minutes, followed by cooling in air to room temperature.

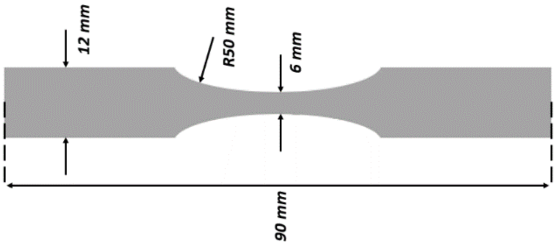

Figure 1: Hourglass-type fatigue specimen

Shot peening was carried out using S330 steel shots having a diameter of 0.84 mm at a peening intensity of 0.47 mmA (SP330) and S110 shots having a diameter of 0.28 mm at an intensity of 0.32 mmA (SP110). Duplex peening (SP3-110) was done by first peening with the larger S330 shots, followed by the smaller S110 shots. Benchmark unpeened specimens (UT-ADI) were mechanically polished to a mirror finish.

Microhardness measurements were done using a Mitutoyo MVK-H2 microhardness testing machine equipped with a Vickers pyramidal diamond indenter, 500 gf load and a dwell time of 10 s. Reported values are the arithmetic mean of a minimum of five measurements.

Two dimensional surface roughness analysis was carried out using a NanoMap-500LS contact profilometer. Fifteen measurements were recorded at a scanning speed of 10 μm/s over a distance of 2500 μm under a contact load of 25 mg.

Rotating bending fatigue tests were carried out on an Italsigma 2TM831 four-point loading rotating-bending fatigue test machine, using a loading ratio R of -1 and a frequency of 60 Hz, in accordance with standard ISO 1143:2010. Each test was stopped when a specimen failed or upon reaching 10^7 cycles, at which point it was considered to be a run-out.

Residual stress measurements were conducted through energy-dispersive synchrotron radiation, on the high-energy beamline ID15A at the European Synchrotron Research Facility (ESRF) in Grenoble, France. A germanium single-crystal detector cooled with liquid nitrogen was utilised as part of the setup. The 2θ value was set to 5°, with the variable being the wavelength of the X-ray source, providing the full X-ray spectra at the selected diffraction angle. The maximum energy throughout these measurements was set at approximately 300 keV.

Results and Discussion

Microhardness and Profilometry

Microhardness measurements show that both SP330 and SP3-110 experienced an increase in surface microhardness of approximately 50% (Figure 2).

Additionally, due to its nature, which involves plastic deformation of the surface, shot peening is expected to bring about an increase in surface roughness. This is also consistent with the results observed in this study (Figure 3), where shot peening using S330 shots brought about an increase in R_a of 675% relative to the ground condition (condition of coupons prior to peening). An increase in surface roughness relative to ground ADI was also observed for duplex shot peened coupons. Duplex shot peening resulted in smaller increase in surface roughness, bringing about a reduction of 26% in R_a relative to SP330 coupons. This reduction in surface roughness can be attributed to peening by the smaller shot, which has a tendency to ‘hammer in’ the peaks generated by the first coarser peening operation, thus levelling the surface. The results are in agreement with previous work by Scuracchio et al. [9], where the lowest roughness was recorded for a secondary peening stage using shots having a diameter of 0.3 mm, which is similar to the nominal diameter of S110 shots utilised in this study.

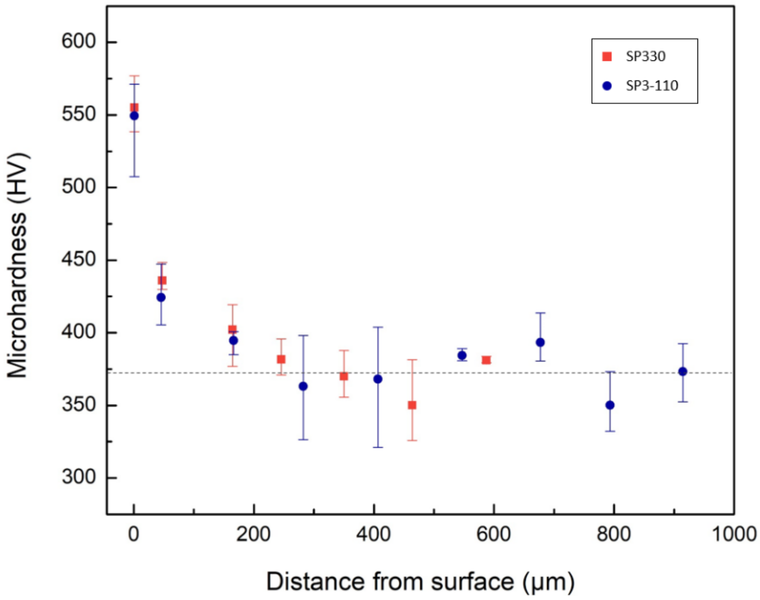

Figure 2: Microhardness profiles for SP330 and SP3-110 coupons. The dotted line represents the microhardness of the ADI microstructure. The error bars represent the maximum and minimum microhardness values recorded.

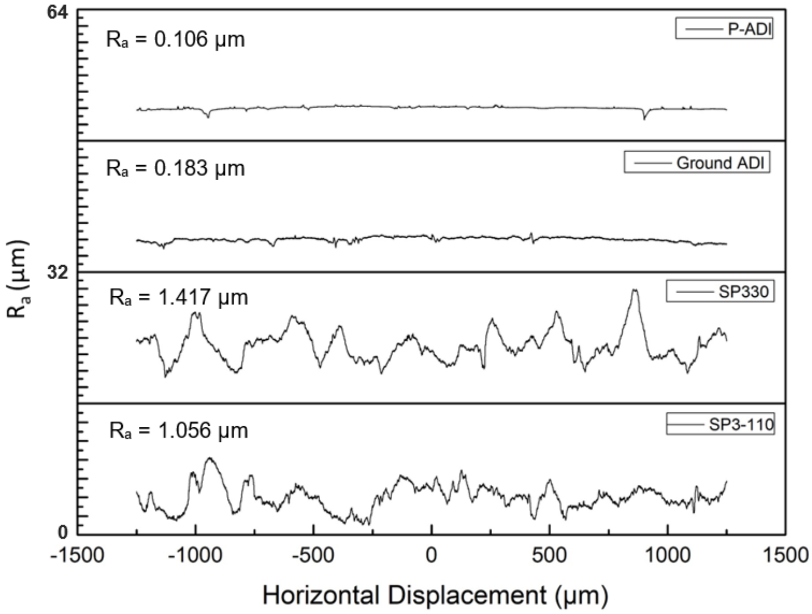

Figure 3: Axial roughness profiles for P-ADI, ground ADI, SP330, and SP3-110. Each profile is plotted on the same scale.

Figure 4(a) shows that ADI in the polished condition reveals a significant degree of residual stresses, which varies from compressive to tensile particularly in the ferritic phase. On the other hand, the surface layers of the austenite making up the ausferrite structure is under tensile stress up to a depth of around 250 μm. Residual stresses in the as-polished specimens can be attributed to machining, heat treatment, or the following grinding and polishing operations. Figure 4(b) displays the residual stress profiles for the austenitic and ferritic phases in SP330. The residual stresses take on the characteristic profile of shot peened materials, comprising of a compressively stressed layer of maximum intensity just beneath the surface, and a tensile stressed layer deeper towards the material core. Overall, shot peening of SP330 coupons brought about maximum compressive stresses of approximately 985 MPa and 785 MPa for austenite and ferrite, peaking in amplitude at depths of around 145 µm and 160 µm below the surface, respectively. This is a result of the plastic deformation induced on the surface, coupled with the strain-assisted transformation of austenite into martensite [3, 10].

Duplex shot peening produced a stress profile similar to that observed for SP330, varying only in terms of the maximum stress amplitude, as illustrated in Figure 4(c). SP3-110 coupons exhibit a maximum compressive stress of 1.17 GPa in the austenitic phase, an increase of approximately 19% over the single shot peened counterpart. Similarly, but to a lesser extent, stress in the ferritic phase increased to a magnitude of around 810 MPa, an increase of roughly 4% over the SP330 condition.

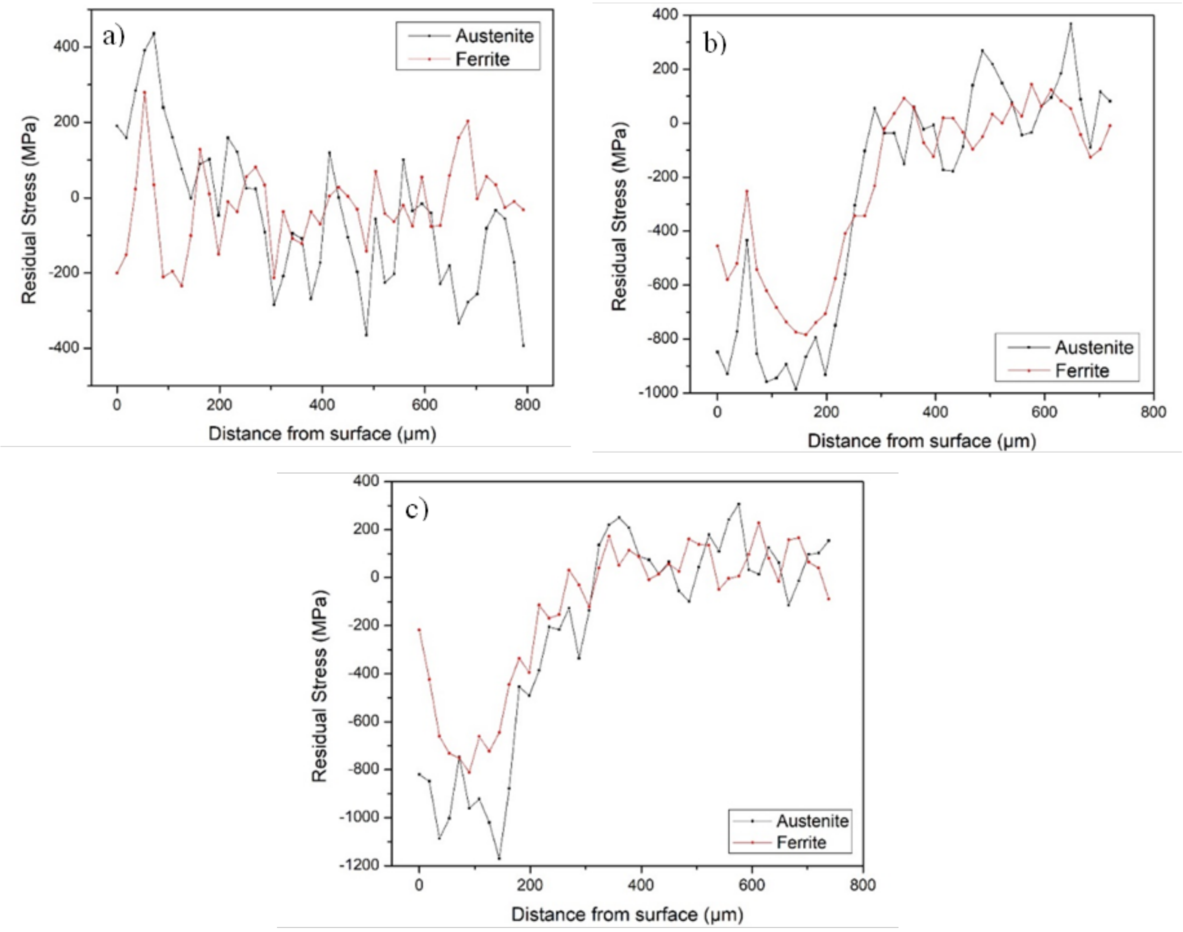

Figure 4: Residual stress-depth profiles for a) P-ADI, b) SP330, and c) SP3-110

Rotating-Bending Fatigue Testing

As shown in Figure 5, the fatigue strength of polished ADI was found to be of 363 MPa. Overall, results reported in literature [3, 5, 11] identify the fatigue limit of ADI as ranging between 200 MPa and 500 MPa, depending on chemical composition, heat treatment, fatigue testing conditions, and numbers of cycles defining the fatigue limit. The fatigue strength is increased to 600 MPa for SP330 coupons, an improvement of approximately 65% over the polished condition. This improvement is a result of the compressive stresses generated through shot peening and the aforementioned solid state transformation, along with work hardening of the ausferrite microsctructure. The detrimental effect brought about by an increase in surface roughness as a result of shot peening, is greatly overshadowed by the positive effects. Reported improvements in fatigue strength following shot peening of ADI fall in the range between 23% [4] to 115% [5], depending on the chemical composition of the as-cast material, the heat treatment employed, the resultant microstructure and phase composition and the shot peening parameters applied.

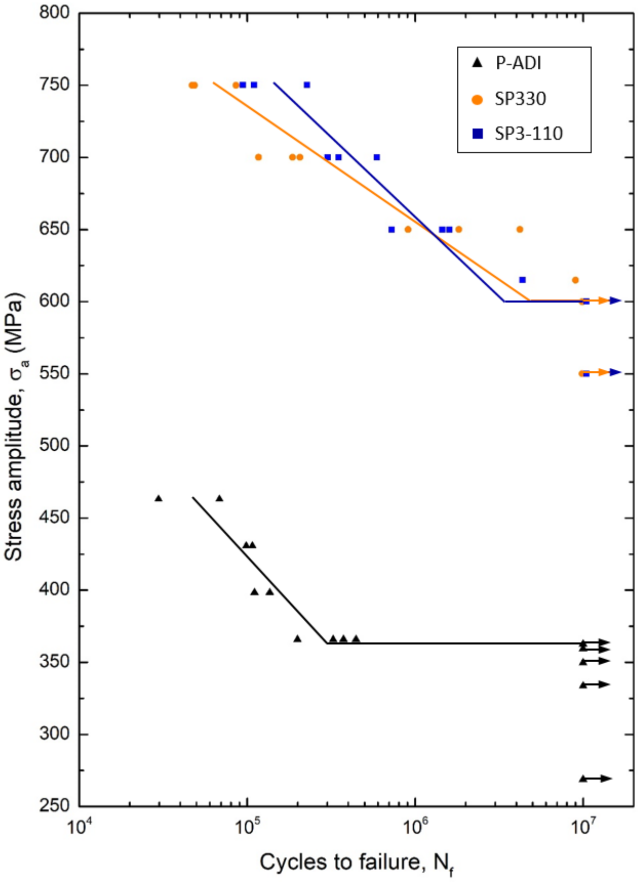

Figure 5: S-N semi-logarithmic curves for P-ADI, SP330 and SP3-110 hourglass-type specimens.

Figure 5 also shows the comparison between shot peened and duplex shot peened specimens. Based on the same principles discussed for SP330, duplex shot peening also brought about significant improvements over P-ADI specimens, with a fatigue strength of 600 MPa. As illustrated in Figure 5, duplex shot peening brought about significant improvements in fatigue life at high stresses. At stress levels of 700 MPa and 750 MPa, the average fatigue life of SP3-110 coupons is extended by approximately 140% over the SP330 condition. This trend was reversed at lower stresses, with SP330 specimens proving to be superior to their duplex counter parts. For a fatigue life of 10^7 cycles, both conditions displayed a fatigue strength of 600 MPa. Due to a reduction in R_a equivalent to around 30%, it was expected that the secondary peening stage would improve the fatigue performance of SP3-110 when compared to SP330 specimens. Despite this, since the surface roughness of SP330 coupons was still significantly low when compared to other results reported in literature, it is postulated that any such improvement may not have been very significant. As outlined in the previous section, duplex shot peening was also effective in obtaining enhanced compressive. Despite this, SP3-110 was not found to be superior throughout.

Conclusions

This study aimed at determining the effect of conventional and duplex shot peening on the fatigue performance of Cu-Ni ADI.

1. Following shot peening, the surface microhardness increased by approximately 50% relative to the as-austempered condition.
3. While shot peening brought about significant roughening, duplex shot peening was successful in reducing this roughness by approximately 30%.
4. Both conventionally and duplex shot peened specimens displayed high magnitudes of compressive residual stresses. This led to an improvement of 65% in fatigue strength over as-treated ADI.
5. The bending fatigue strengths of both groups of shot peened specimens are within the ranges specified in the 'AGMA – Austempered Ductile Iron for Gears' technical sheet [12], verifying their potential as viable gear materials for automotive applications.
6. At high stresses, duplex shot peening brought about significant improvements in fatigue life relative to conventionally shot peened specimens.

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