Effect of shot peening process on fatigue behavior of an alloyed austempered ductile iron

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Abstract: Shot peening is one of the most common surface treatments to improve the fatigue behavior of metallic parts. In this study the effect of shot peening process on the fatigue behavior of an alloyed austempered ductile iron (ADI) has been studied. Austempering heat treatment consisted of austenitizing at 875°C for 90 min followed by austempering at three different temperatures of 320, 365 and 400°C. Rotating-bending fatigue test was carried out on samples after shot peening by 0.4 – 0.6 mm shots. XRD and SEM analysis, micro hardness and roughness tests were carried out to study the fatigue behavior of the samples. Results indicate that the fatigue strengths of samples austempered at 320, 365 and 400°C are increased by 27.3%, 33.3% and 48.4%, respectively, after shot peening process.

Key words: austempered ductile iron; shot peening; fatigue strength; roughness

Austempered Ductile Iron (ADI) is increasingly becoming an economic alternative for steel parts [1], because of its excellent combination of mechanical properties such as high wear resistance, tensile strength, fatigue strength and ductility. Reliable design against fatigue failure requires proper education and supervised experience in structural engineering, mechanical engineering or materials science. Designing to keep stress below threshold of fatigue limit and instructing the users to inspect the parts periodically are principal approaches to life assurance for different parts [2].

The materials' toughness has a considerable contribution to improvement of fatigue strength. Austempering heat treatment consists of austenitizing in the temperature range of 900±50°C and quenching and isothermal holding in the austempering temperature range of 250-400°C. During the austempering heat treatment, ADI undergoes a two-stage transformation process. In the first stage the austenite decomposes into ferrite and carbon-enriched austenite which is stable at room temperature [3]. The obtained microstructure is known as ausferrite which effectively enhances the toughness of alloy. Moreover, it is known that shot peening is one of the most common surface treatments to improve the fatigue strength of the metallic products. Such treatment involves blasting the surface of the products with steel or glass shots at high velocity. Basically, shot peening creates compressive residual stress zone beneath the blasted surface which can be measured using different techniques such as hole drilling, X-ray and neutron diffraction [4]. This compressive residual stress can reduce the tensile stress that persuades the fatigue crack initiation and propagation on the surface.

Furthermore, shot peening can work harden and change the dislocation density just near the surface layer that can be studied by measuring the full width at half maximum (FWHM) obtained from XRD patterns. This work hardened layer delays the fatigue crack initiation and propagation [5].

Although shot peening treatment increases the surface roughness of the samples and seems to deteriorate the fatigue strength by increasing the density of crack nucleation sites, but the beneficial effects of compressive residual stresses and work hardened layer are superior [5,6]. When an ADI part is shot peened, its surface microstructure (ausferrite) is stressed above its yield strength and both ferrite and high carbon austenite undergo plastic deformation. Ferrite work hardens and its dislocation density increases. But high carbon austenite, that is mechanically unstable, transforms to martensite through TRIP (Transformation Induced Plasticity) effect. Thus it is expected to have mainly martensite in near surface regions instead of austenite after shot peening [7,8].

This research aims to study the effect of shot peening treatment on the fatigue behavior of an alloyed ADI considering the microstructural changes.

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Received: 2010-04-29; Accepted: 2011-05-20

CLC numbers: TG145.5 Document code: A Article ID: 1672-6421(2011)03-325-06
1 Experimental procedure

1.1 Melt production and casting

The material used in this study was an alloyed ductile iron with chemical composition given in Table 1. The ductile iron was produced in a single frequency induction furnace of 100 kg capacity and cast into standard Y-blocks using plunging method.

Table 1: Typical chemical composition of the casting (wt. %)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Mo</th>
<th>Cu</th>
<th>Ni</th>
<th>S</th>
<th>Ti</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt. %</td>
<td>3.51</td>
<td>3.1</td>
<td>0.19</td>
<td>0.24</td>
<td>0.49</td>
<td>0.59</td>
<td>0.006</td>
<td>0.012</td>
<td>0.034</td>
</tr>
</tbody>
</table>

1.2 Heat treatment

Impact, tensile and fatigue test specimens were prepared from the bottom section of the blocks to avoid the defects present in the above region. First, all the impact test specimens were austenitized at 875°C for 90 min and then austempered at three different temperatures of 320, 365 and 400°C for the times ranging from 10 to 1,440 min to determine the austempering time to gain the optimum properties. Consequently, all tensile and fatigue test specimens were heat treated in determined optimum austempering times at each austempering temperature.

1.3 Optical and mechanical tests

To identify the matrix structure and morphology, the samples were examined using Olympus PMG3 optical microscope. Moreover, micro hardness tests were carried out using MDPEL hardness machine and un-notched charpy impact tests were conducted using a Roell Amsler testing machine with 300J capacity. Tensile tests were carried out on a computer-controlled servohydraulic machine (Adamel) at a crosshead speed of 2.5 mm·s⁻¹. The hardness test was performed using ESEWAY hardness machine in Brinell scale. Finally the microstructure and fracture surfaces of samples were analyzed by using an Oxford Cam Scan MV 2300 model scanning electron microscope.

1.4 Shot peening and fatigue test

Fatigue specimens were machined accurately from standard Y-blocks according to DIN 50113 standard. Test specimens were austenitized and austempered at optimum austempering times and then divided into two groups, with and without shot peening.

Shot peening treatment was carried out on Gutmann™ Shot peening machine under the conditions summarized in Table 2. Rotating bending fatigue tests were performed up to 10⁷ cycles using a Roell Amsler UBM 200 testing machine.

1.5 Measurement of the surface roughness and the volume fraction of austenite

Surface roughness test was conducted according to DIN 4768 standard with TIME TR 100 roughness tester in Ra scale (roughness average). Brucker-Axe D8 Advance X-ray diffractometer was used to measure the volume fraction of high carbon austenite as well as its carbon content, using monochromated CuKα radiation at 50 kV and 30 mA according to ASTM E975-84 standard. Scanning was performed in the 2θ range of 30 to 100°. The areas under the peaks were measured using the Eva™ software. The carbon content of austenite was calculated from the angular position of the austenite peaks and the volume fraction of austenite was determined from the integrated area under the austenite and ferrite peaks [10, 11]. Peaks from the (200), (220) and (311) planes of austenite and the (200), (211), and (220) planes of ferrite were used to minimize the error from the preferred orientation of phases.

2 Results and discussion

Figure 1 shows the bulls-eye microstructure of as-cast specimen containing pearlite and ferrite. Microstructural features are summarized in Table 3. Appropriate casting process using plunging method resulted in high nodularity and nodule count.

Table 2: Shot peening conditions

<table>
<thead>
<tr>
<th>Almen intensity (A)</th>
<th>Coverage (%)</th>
<th>Shot size (mm)</th>
<th>Shot hardness (HRC)</th>
<th>Rotating speed (rev·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>100</td>
<td>0.6–0.8</td>
<td>48–52</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3: Microstructural features of as-cast ductile iron

<table>
<thead>
<tr>
<th>Microstructure</th>
<th>Hardness (HB)</th>
<th>Nodule count (mm⁻²)</th>
<th>Nodularity (%)</th>
<th>Nodule diameter (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearlite 55%</td>
<td>255</td>
<td>200</td>
<td>&gt; 90</td>
<td>25</td>
</tr>
<tr>
<td>Ferrite 45%</td>
<td>255</td>
<td>200</td>
<td>&gt; 90</td>
<td>25</td>
</tr>
</tbody>
</table>

According to the impact test results, the optimum austempering time is about 105 min for austempering temperature of 320°C and 90 min for both 365 and 400°C. Mechanical properties of specimens austempered at 320 and 400°C for optimum austempering times are compared in Table 4 for instance.
Because of the high silicon content of the castings (3.1 wt.%) and high austempering temperature, it is reasonable that no carbides would exist in the microstructure. Moreover, no considerable untransformed austenite (UAV) was observed in the microstructure because the austempering were carried out within the heat treatment processing window.

Figure 2 illustrates the S-N curves obtained for base ductile iron and austempered specimens before and after shot peening operation.

According to the results, the fatigue strength of base ductile iron at $10^7$ cycles is about 250 MPa which increases after austempering at each austempering temperatures. This is because of the ausferrite formation due to the austempering treatment. Contrary to the pearlite-ferrite microstructure, high carbon austenite can partially absorb the applied fatigue stress and can be work hardened so that it tolerates higher stress to some extent.

According to the results, the fatigue strengths of ADI austempered at 320, 365 and 400°C are increased by 10%, 20% and 44%, respectively, in comparison with that of base ductile iron.

The fatigue strength of base ductile iron at $10^7$ cycles is increased by 40% after shot peening because of the matrix work hardening which takes place along the microstructure. Also the fatigue strengths of the specimens austempered at 320, 365 and 400°C are increased by 27.3%, 33.3% and 48.4%, respectively, after shot peening. Results indicate that shot peening is more effective in enhancement of the fatigue strength at higher austempering temperatures.

The volume fractions of the high carbon austenite in specimens austempered at 320, 365 and 400°C were measured before and after shot peening which are given in Table 6. Also the XRD patterns before and after shot peening process for samples austempered at two temperatures of 365 and 400°C are shown in Fig. 4. The comparison of patterns for each austempering temperature shows that the austenite peaks almost disappear after shot peening, because the high carbon austenite is transformed to martensite through a TRIP effect.

Measurements show that there is still 6.6% of austenite present in the microstructure of the samples which were austempered at 400°C, after shot peening.

Both ferrite and high carbon austenite at the surface layer underwent severe plastic deformation after shot peening.

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**Table 4: Mechanical properties of austempered specimens**

<table>
<thead>
<tr>
<th>Austempering temperature (°C)</th>
<th>Hardness (HB)</th>
<th>Elongation (%)</th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>320</td>
<td>300</td>
<td>4.3</td>
<td>1,060</td>
<td>805</td>
</tr>
<tr>
<td>400</td>
<td>260</td>
<td>7.8</td>
<td>820</td>
<td>590</td>
</tr>
</tbody>
</table>

**Table 5: Fatigue strength of all tested specimens at $10^7$ cycles**

<table>
<thead>
<tr>
<th>Base ductile iron</th>
<th>Austempering temp. (°C)</th>
<th>Before shot peening (MPa)</th>
<th>After shot peening (MPa)</th>
<th>Increase in comparison with base ductile iron (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>320</td>
<td>365</td>
<td>400</td>
</tr>
<tr>
<td>Before shot peening</td>
<td>250</td>
<td>275</td>
<td>300</td>
<td>310</td>
</tr>
<tr>
<td>After shot peening</td>
<td>350</td>
<td>350</td>
<td>400</td>
<td>460</td>
</tr>
<tr>
<td>Increase (%)</td>
<td>40</td>
<td>27.3</td>
<td>33.3</td>
<td>48.4</td>
</tr>
</tbody>
</table>

**Table 6: Measured volume fraction of high carbon austenite before and after shot peening**

<table>
<thead>
<tr>
<th>Austempering temp. (°C)</th>
<th>Before shot peening (%)</th>
<th>After shot peening (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>320</td>
<td>12.6</td>
<td>0</td>
</tr>
<tr>
<td>365</td>
<td>17.3</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>22.4</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Consequently austenite transformed to martensite and the dislocation density of the ferrite plates increased substantially. The XRD results show that the FWHM and integrated area under the ferrite peaks increased after shot peening. FWHM values of (200) peak for ferrite are given in Table 7.

![XRD patterns for specimens austempered at (a) 365°C and (b) 400°C](image)

**Fig. 4: XRD patterns for specimens austempered at (a) 365°C and (b) 400°C**

According to Tables 7 and 8, the positions of the ferrite and martensite peaks change after shot peening which is assumed to be because of the applied stresses through the shot peening process. The peaks broadenings are due to the non-uniform strain within the microstructure whereas the peaks shift as a result of a change in lattice parameter of ferrite and austenite because of the residual compressive stresses after shot peening [10]. According to Fig. 4, the increased integrated area under ferrite peaks is due to martensite formation where its related peaks appear at the almost same angular positions as to ferrite.

**Table 7: Measured FWHM values of (200) peaks for ferrite before and after shot peening**

<table>
<thead>
<tr>
<th>Austempering Temp.</th>
<th>Before shot peening</th>
<th>After shot peening</th>
</tr>
</thead>
<tbody>
<tr>
<td>320°C</td>
<td>0.506</td>
<td>0.788</td>
</tr>
<tr>
<td>365°C</td>
<td>0.537</td>
<td>0.589</td>
</tr>
<tr>
<td>400°C</td>
<td>0.615</td>
<td>0.661</td>
</tr>
</tbody>
</table>

According to Tables 7 and 8, the positions of the ferrite and martensite peaks change after shot peening which is assumed to be because of the applied stresses through the shot peening process. The peaks broadenings are due to the non-uniform strain within the microstructure whereas the peaks shift as a result of a change in lattice parameter of ferrite and austenite because of the residual compressive stresses after shot peening [10]. According to Fig. 4, the increased integrated area under ferrite peaks is due to martensite formation where its related peaks appear at the almost same angular positions as to ferrite.

**Table 8: Diffraction angle (2θ) of ferrite and martensite peaks before and after shot peening**

<table>
<thead>
<tr>
<th>Austempering temp.</th>
<th>2θ before shot peening (110)</th>
<th>2θ before shot peening (200)</th>
<th>2θ before shot peening (211)</th>
<th>2θ after shot peening (110)</th>
<th>2θ after shot peening (200)</th>
<th>2θ after shot peening (211)</th>
</tr>
</thead>
<tbody>
<tr>
<td>320°C</td>
<td>44.71</td>
<td>64.85</td>
<td>82.39</td>
<td>44.79</td>
<td>64.95</td>
<td>82.48</td>
</tr>
<tr>
<td>365°C</td>
<td>44.70</td>
<td>64.88</td>
<td>82.32</td>
<td>44.71</td>
<td>64.98</td>
<td>82.41</td>
</tr>
<tr>
<td>400°C</td>
<td>44.71</td>
<td>64.83</td>
<td>82.36</td>
<td>44.74</td>
<td>65.00</td>
<td>82.31</td>
</tr>
</tbody>
</table>

Fatigue cracks usually nucleate from the surface of parts because of the high stress concentration on this region. Before shot peening, the surface is prone to crack nucleation and growth. However, as mentioned before, higher stress is required for a crack to be formed and propagated after shot peening, because of the residual compressive stress created on the surface and presence of martensite. Moreover, when austenite transforms to martensite due to shot peening process, the FCC crystalline lattice changes to BCT which accompanies with a local volume increase at the surface [12]. This volume change leads to further local compressive residual stress that in turn retards the fatigue cracks nucleation and growth [9,13].

According to the previous studies [14, 15], fatigue cracks initiate at the interface between graphite nodules and the matrix or at pores. Then the fatigue crack follows the path of the least resistance through the matrix between nodules. In shot peened specimens austempered at 320 and 365°C, a nucleated fatigue crack propagates through the ferrite plates and martensite packets. At high stresses when the fatigue crack reaches to martensite it propagates quickly whereas at low stresses it changes its direction to ferrite which is softer [16]. However, in shot peened specimens austempered at 400°C, besides a fatigue crack nucleation delay, presence of high carbon austenite (6.6%) increases the fatigue life, either. In these specimens, when a propagating fatigue crack reaches to austenite, there will be a regional TRIP effect at crack tip because of stress concentration. Consequently, high carbon austenite transforms to martensite which accompanies with local volume increase at crack tip. This leads to compressive stress, decreases the crack propagation rate and further increases the fatigue strength [17, 18].

The roughness of the samples increases after shot peening which leads to the deterioration of the fatigue strength, because the surface of the sample becomes prone to nucleation of cracks. However results show that work hardening and compressive residual stress are overwhelming and finally the fatigue strength improves.

In this study the roughness value (Ra) of the primary samples ia about 0.4 μm which is increased to 4.2 μm after shot peening. However it has a negligible effect on the fatigue strength compared with that of created martensite and residual stress on the surface of the job.

Micro hardness measurements were conducted on the cross section of specimen austempered at 400°C to determine the depth of martensite formed during the shot peening operation. Figure 5 shows how the hardness of the shot peened specimen varies by distance from the surface.
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August 2011

It can be seen from Fig. 5 that the hardness decreases from the surface to the core of samples. Higher micro hardness just under the shot peened surface is because of austenite transformation into martensite and the ferrite work hardening which occurred in this region. According to the profile, the depth which is affected by shot peening is estimated to be about 70 μm.

It must be mentioned that shot peening operation would not be much effective in enhancement of fatigue strength for stresses over 500 MPa. At higher stresses, the difference in the fatigue strength before and after shot peening is less than that of lower stresses. This is because of stress relaxation phenomenon that occurs at high stresses in which fatigue crack nucleation happens earlier and nucleated crack grows rapidly so that the final fracture occurs at lower cycles.

Figures 6 and 7 show the SEM images of fracture surfaces for fatigue specimens in which the fatigue crack nucleation zone (N), fatigue crack growth zone (G) and final fracture zone (F) are shown. Figures 6(a) and 6(b) show the fracture surfaces of specimens austempered at 320°C before and after shot peening. It is clear that, the fracture surfaces are nearly similar to the fact that they have a different strength and fatigue life. Study on the fracture surfaces of the samples before shot peening showed the fracture mode to be ductile containing ductile dimples. However, in shot peened specimens, there were no clear dimples so the fracture mode was brittle, especially near the surface.

Figure 7 shows ductile fracture dimples around a graphite nodule in the specimen austempered at 365°C for 90 min. This specimen has failed after 480,000 cycles under the stress of 375 MPa before shot peening. In contrast, Figure 8 shows fracture mode near the surface in a shot peened specimen which were austempered at 400°C for 105 min. This specimen failed after 959,700 cycles under the stress of 485 MPa and there was no clear dimple around the graphite nodule and the fracture mode was brittle. This proves the probability of existence of martensite in the matrix induced by shot peening process.
3 Conclusions

(1) The fatigue strengths of specimens austempered at 320, 365 and 400°C at $10^7$ cycles are increased by 27.3%, 33.3% and 48.4%, respectively, after shot peening.

(2) According to XRD patterns shot peening process leads to transformation of austenite to martensite and based on micro hardness profile the affected depth is estimated to be about 70 μm.

(3) For specimens austempered at 400°C almost 16% of high carbon austenite transforms to martensite and 6.6% is still remaining. The existence of 6.6% high carbon austenite increases the fatigue strength and life in these specimens.

(4) Quasi-cleavage fracture near the surface in shot peened specimens without clear dimples is in agreement with XRD results confirming the formation of martensite after shot peening.

References


