The initiation and propagation of fatigue cracks in the shot-peened surface of two high-strength aluminium alloys

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SYNOPSIS Two high strength aluminium alloys have been studied, 7010 with a composition (wt%) of Al-2Cu-2.5Mg-6Zn-0.15Zr and 8090 which is a newly developed Al-Li alloy with composition Al-2.5Li-1.2Cu-0.7Mg-0.12Zr. All alloys were notched (Kt=2.03) and some shot peened to an intensity of 8-10C on the Almen scale. The base of the notch was carefully mechanically polished, in the case of the peened specimens in order to remove the surface roughness without modifying the surface residual compressive stress. The specimens were tested in reversed bending and interrupted at regular intervals to enable replicas to be taken of the base of the notch. When a crack had been initiated as indicated by the replicas and had reached a depth of 1mm, the progress of the crack was followed by a potential drop method. Crack growth curves show that in both alloys the crack is initiated sooner in the peened surface than in the unpeened surface, but that the propagation is much retarded by the compressive stress, resulting in a much longer life of the peened specimens. The initiation of cracks in the peened surface is associated with surface damage arising during the peening process.

1 INTRODUCTION

Shot-peening is widely used as a surface treatment for improving the fatigue properties of engineering components. This is particularly so in the aircraft industry where structural components fabricated in high-strength aluminium alloys are shot-peened as a matter of course. The effects of shot-peening are three-fold:
(a) it roughens the surface.
(b) it work hardens the surface, and
(c) it develops a compressive stress in the surface.

Earlier work showed that the work hardening effect on aluminium alloys had little influence on the fatigue behaviour (1). The main component in improving the fatigue life is the residual compressive stress. However, careful polishing of the surface to reduce the roughness without significantly affecting the compressive stress produced a small further increase in fatigue life. In fretting-fatigue tests (1) the polishing produced a reduction in fatigue life indicating that a rough surface gives a better performance under these conditions. The specimens in this work were shot-peened to an intensity of 12-16A on the Almen scale using a steel shot size of 0.84mm. In the aircraft industry much heavier shot-peening is often employed and this may lead to increased surface damage. There is no doubt that shot-peening produces surface damage, an obvious feature of which is the production of folds on the surface due to the local plastic deformation or impact extrusion of material parallel to the surface (2). The degree of folding is a function of the impact energy and also the ductility of the material, which in aluminium alloys is determined by the heat treatment (3).

The present investigation is concerned with the effect that heavy shot-peening has on the initiation and subsequent propagation of a fatigue crack in two high-strength aluminium alloys, one of which, 7010, is already in use for aircraft components, and the second of which, 8090, has wide potential applications.

2 EXPERIMENTAL

The compositions of the two alloys are shown in Table 1. The material was supplied in the form of 25mm rolled plate which was solution heat-treated for 30 minutes at 475°C for 7010 and at 530°C for 8090. It was water-quenched and then stretched to give a permanent elongation strain of 2.5%. The 7010 alloy was finally aged at 170°C for 6h. and the 8090 at 190°C for 16h. The resultant mechanical properties are given in Table 2. Rectangular specimens were machined from the plate with the dimensions 100x20x25mm. On one of the 100x20 faces i.e. the rolled surface, a notch was machined at the midpoint with a depth of 6.25mm and a generous tip radius of 3mm, giving a theoretical stress concentration factor of 2.03. The tests were carried out in a servo-hydraulic machine in reverse bending with a stress ratio R of 0.1 and a frequency of 6.7Hz. The shot-peened specimens were peened to an intensity of 8-10C on the Almen scale with 1.40mm diameter steel balls of hardness 45 to 52 Rc. The base of the notch on all of the specimens was carefully polished mechanically to give a smooth surface which then enabled crack initiation to be followed by taking surface replicas with cellulose acetate film. Replicas of the surface were made every 500 cycles in the early stages. The crack always initiated at the base of the notch: in the case of the shot-peened specimens the initiation site was usually from a remnant of peening damage. When the fatigue crack was
well established it was then monitored by an electrical potential drop method. The potential drop system was calibrated by breaking open a number of specimens at various stages of their fatigue lives and comparing the depth of the crack to the potential difference across the work faces.

Most of the fatigue tests were continued to failure. However, a number of tests were interrupted in the early stages to correlate the early crack growth with the information from the replicas. This was achieved by taking metallographic sections through the crack which enabled the shape and depth of the initial cracks to be measured. A relation was developed between depth of crack and the length of crack on the surface. This allowed the observation on the replicas to be translated into crack depths. In other tests the specimen was sectioned to give information on the initiation site and the propagation of the crack and also the nature of the sub-surface damage in the case of the shot-peened specimens.

3 RESULTS

The crack growth curves are shown in Figures 1-4; those in Figures 1 and 2 are on a log scale of stress cycles whereas Figures 3 and 4 show the initial stages of crack growth plotted on a linear scale. The general effect of peening in both 7010 and 8090 alloys has been to significantly prolong the fatigue life.

The fatigue crack path in 7010 alloy was relatively straight and flat, but in 8090 alloy the crack path is tortuous since slip in this alloy is very planar and fatigue cracking follows the intense shear bands (4). Figure 5 is a section through the base of the notch in a specimen of 8090 in the unpeened condition and shows the tortuous crack path.

Shot peening the alloys before fatigue testing produces a highly deformed and work hardened layer at the surface. In the case of the 8090 alloy this work hardened layer with its high dislocation content disperses the planar slip so that crack propagation through the surface layers is now relatively straight (Figure 6). However, once the crack has passed through the deformed layer it reverts to its highly faceted course (Figure 6).

Shot peening also introduces damage in that surface layers are folded over one another and forced into the surface of the specimen. Figure 7 is a section through such a damaged region in shot peened 7010 alloy, and it can be seen that fatigue cracks grow from such regions. Figure 8 is a plan view of the base of the notch in 8090; the circular region is a remnant of the peening damage (the rest of the surface has been lightly polished) and a fatigue crack can be clearly seen running from this region.

4 DISCUSSION

The general effect of heavy shot peening (Almen 8-10C) on both the high strength alloys has been to introduce a large number of surface defects, but in spite of this the fatigue lives of both alloys have been considerably increased at most stress levels (Figures 1 and 2). At equivalent applied stresses the fatigue crack growth in the 8090 alloy is significantly slower than in 7010. This slower crack growth in Al-Li based alloys is due to the intense planar slip that takes place causing fatigue cracking to follow the (111) slip planes. The result is a highly faceted fatigue fracture surface (Figure 6) leading to early closure of the crack faces during the compression part of the fatigue cycle, which in turn reduces the effective stress intensity range that the crack tip experiences. The early closure and rubbing of the fracture facets during fatigue also causes considerable fretting of the crack surfaces so that black fretting debris flows from the mouth of the fatigue crack during testing.

Examination of the early stages of crack growth (Figures 3 and 4) shows that in the first 20,000 cycles of stress the crack is already in existence in the shot peened specimens, whereas a crack is not detected in the unpeened specimens until many more cycles have elapsed. The subsequent crack propagation in all cases, except the 8090 alloy tested at 138MPa which will be referred to later, was then much slower in the shot peened specimens so that there is soon a cross-over in the curves. This very slow rate of crack propagation during the initial 0.5mm of cracking in the shot peened samples can be attributed to the high residual compressive stresses in the surface layers.

The early initiation of cracks in the shot peened specimens is a result of the surface damage caused by the heavy shot peening used in the current investigation. In all the specimens examined by the replica technique the source of the crack was always sited at a region of intense surface folding: such a region is not removed by light polishing of the peened surface and remains as a dark circular region (Figure 8). On the peened sample there are, of course, numerous defects of this type and it is found that fatigue cracks nucleate at a large proportion of them. Each of these grows slowly through the surface layers with their high compressive stresses but then eventually link up to form a single macro-crack as the number of applied stress cycles is increased.

Returning now to the earlier observation that shot peening the 8090 alloy does not appear to improve the fatigue properties when tested at 138MPa (e.g. see Figure 4). In the Al-Li based alloy shot peening will produce two effects in the surface layers: residual compressive stresses which reduce the crack propagation rate, and a highly deformed work hardened microstructure which prevents fatigue faceting and hence increases the crack propagation rate. The net effect on fatigue crack propagation will be a balance between these two effects. At low applied stresses the residual compressive stresses in the surface will dominate and crack propagation through the surface layers of the shot peened samples will be much slower than in the unpeened case. High applied stresses will counterbalance a considerable portion of the surface compressive stresses and the microstructural effect now becomes of importance. The final result is very little difference in fatigue properties between peened and unpeened 8090 alloy when tested at high stress levels.
CONCLUSIONS

1. Shot peening the alloys 7010 and 8090 to a large intensity (Almen 8-10C) introduces high surface compressive stresses along with many "fold-like" defects.

2. Fatigue cracks initiate at the surface defects introduced by the peening but due to the presence of the compressive stresses in the surface, propagation of these cracks is very slow over the first 0.5mm of cracking.

3. Fatigue cracks in unpeened samples initiate at a later stage than in peened samples, but once initiated they grow rapidly.

4. The net effect of observations 2 and 3 is for heavy peening of 7010 and 8090 to significantly improve the fatigue performance, particularly at low applied stresses.

5. The improvement of fatigue life by peening 8090 appears to be small at high applied stresses. This may be due to the heavily deformed layer in the shot peened samples preventing faceted growth and hence speeding up crack growth during the initial stages of fatigue.

ACKNOWLEDGEMENTS

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REFERENCES


Table 1 Compositions (wt/%) of alloys used in the investigation

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<tr>
<th>Alloy</th>
<th>Li</th>
<th>Zn</th>
<th>Mg</th>
<th>Cu</th>
<th>Zr</th>
<th>Fe</th>
<th>Si</th>
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<td>7010</td>
<td></td>
<td>5.96</td>
<td>2.26</td>
<td>1.59</td>
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<td>8090</td>
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<td></td>
<td>0.76</td>
<td>1.12</td>
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Table 2 Mechanical properties of alloys used in the investigation

(Tested in the L direction)

<table>
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<tr>
<th>Alloy</th>
<th>0.2% Proof Stress (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
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<tr>
<td>7010</td>
<td>450</td>
<td>515</td>
<td>7</td>
</tr>
<tr>
<td>8090</td>
<td>450</td>
<td>497</td>
<td>5</td>
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Crack length versus number of stress cycles for alloy 7010 at different stress levels. The open symbols are for unpeened specimens, the solid symbols for shot-peened specimens

- 145MPa
- 130MPa
- 105MPa

* = position where several initiated cracks in the shot-peened specimens link up to form a single macrocrack

Fig 2 Crack length versus number of stress cycles for alloy 8090 at different stress levels. The open symbols are for unpeened specimens, the solid symbols for shot-peened specimens

- 138MPa
- 122MPa
- 114 MPa
- 105MPa

* = position where several initiated cracks in the shot-peened specimens link up to form a single macrocrack

Fig 3 Early stages of crack length versus number of stress cycles (linear scale) for alloy 7010 (symbols as in Fig 1)

Fig 4 Early stages of crack length versus number of cycles (linear scale) for alloy 8090 (symbols as in Fig 2)
Fig 5  Optical micrograph of section through base of specimen notch for alloy 8090 showing faceted nature of cracking in unpeened material (photographically reduced to 80 per cent)

Fig 6  Optical micrograph of section through base of specimen notch for alloy 8090 in the peened condition. Crack growth is relatively flat through the deformed surface layers, but then reverts to its highly faceted nature (photographically reduced to 80 per cent)

Fig 7  Optical micrograph of section through base of specimen notch for alloy 7010 in the peened condition, showing folding defects in the surface and fatigue cracks running from these defects (photographically reduced to 80 per cent)

Fig 8  Replica taken from surface of 8090. The peened surface has been lightly polished to leave only the surface defects. Fatigue cracks can be seen growing from these defects (photographically reduced to 80 per cent)