The Interaction Between Shot-Peening and Heat Treatment on the Fatigue and Fretting-Fatigue Properties of the High Strength Aluminium Alloy 7075

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ABSTRACT

Earlier work had shown that shot-peening an Al-4Cu-1Mg alloy in the SHT condition and then ageing, produced a material which was completely insensitive to fretting damage. The Al-6Zn-3Mg 7075 alloy studied here proved to be little affected by fretting after peening in the fully aged condition. In this case shot-peening in the SHT condition followed by ageing produced a material relatively insensitive to fretting damage but of lower fatigue strength. Shot-peening after a two-stage ageing treatment again produced a material whose fatigue and fretting-fatigue curves were virtually the same but slightly lower than those of the single-stage aged alloy. Shot-peening between the two ageing treatments in the two-stage ageing process resulted in very low fatigue and fretting-fatigue strengths comparable with those of the unpeened material.

INTRODUCTION

Shot-peening is widely used as a method for improving the fatigue properties of engineering components, particularly in the aircraft industry. 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 indicates that the last effect is the most beneficial in resisting fatigue or fretting-fatigue failure (1), although surface roughening also produces a slight improvement in fretting-fatigue behaviour. Current work shows that fatigue cracks are initiated much sooner in a shot-peened surface than in an un-peened surface, and indeed may be present as a result of the shot-peening (2). The cracks propagate much more slowly as a result of the compressive stress and the fatigue life is much increased. However, the compressive stress tends to fade under the cyclic stressing due to shake-down. If fading of the compressive stress could be prevented then even longer fatigue lives would be the result. In earlier work on the alloy Al-4Cu-1Mg (2014A) it was found that by carrying out the shot-peening operation when the alloy was in the solution treated (SHT) condition, followed by the normal ageing process, the material became insensitive to fretting, i.e. the fatigue curves in normal fatigue and fretting-fatigue were identical, and also the fatigue
lives were much longer at the higher stresses (3). The ageing process reduced the level of the compressive stress but it was found to be more or less constant with no fading. Part of the improvement, however, can be attributed to the different micro-structure in the surface. The shot-peening increases the density of dislocations in the surface which then nucleate a fine dispersion of $\text{S'}(\text{Al}_2\text{CuMg})$ precipitates. Since the aluminium alloy Al-6Zn-3Mg (7075) is widely used in the aircraft industry it was decided to investigate various combinations of shot-peening and heat treatment to see if beneficial results in fatigue and fretting-fatigue behaviour would arise.

EXPERIMENTAL

The analysis of the alloy used in this investigation is shown in Table 1.

Table 1 Chemical composition of alloy 7075 (wt.%)  

<table>
<thead>
<tr>
<th>Cu</th>
<th>Mg</th>
<th>Si</th>
<th>Fe</th>
<th>Mn</th>
<th>Ni</th>
<th>Zn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.76</td>
<td>2.65</td>
<td>0.14</td>
<td>0.21</td>
<td>0.03</td>
<td>0.03</td>
<td>5.40</td>
<td>balance</td>
</tr>
</tbody>
</table>

The test specimens were in the form of rod shaped specimens 356 mm in length and 9.5 mm in diameter. A gauge length was produced by machining two parallel flats in the centre of the specimen with a generous fillet radius of 50 mm reducing the thickness at this point to 6.4 mm. The combination of heat treatment and shot-peening given to the alloy are shown in Table 2. In every case where shot-peening was applied the Almen intensity was 0.012-0.016 A using steel shot of size 0.84 mm.

Table 2 Combinations of heat treatment and shot-peening

<table>
<thead>
<tr>
<th>Description</th>
<th>Heat Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot peened after single stage ageing</td>
<td>SHT $460^\circ$C WQ, aged 12h at $135^\circ$C</td>
</tr>
<tr>
<td>Shot peened after two stage ageing</td>
<td>SHT $460^\circ$C, aged 6h at $110^\circ$C, AC aged $175^\circ$C</td>
</tr>
<tr>
<td>Shot peened in SHT followed by single stage ageing</td>
<td>SHT $460^\circ$C WQ, refrigerated, peened, aged 12h at $135^\circ$C</td>
</tr>
<tr>
<td>Shot peened between two stage ageing</td>
<td>SHT $460^\circ$C WQ, aged 6h at $110^\circ$C, AC peened, aged $175^\circ$C</td>
</tr>
</tbody>
</table>

WQ = water quench  AC = air cool  SHT = solution heat treat
The specimens were tested in a four-point loading rotating-bending fatigue machine. Where fretting was applied this was achieved by clamping a pair of bridges on to the gauge length by means of a proving ring. The clamping pressure was adjusted to 32 MPa. The frequency used in the tests was 25 Hz. S-N curves were obtained for the specimens in both plain fatigue and fretting fatigue. S-N curves were also obtained for the alloy in the single stage ageing condition without shot-peening, again in plain fatigue and fretting-fatigue.

The stress fields produced by the shot-peening operations were measured using the two exposure X-ray technique with a Siemens Kristalloflex diffractometer using CuK$_\alpha$ radiation. The stress profiles were obtained by progressive etching away of the surface, the stress measurements being corrected for the material removed. These profiles are shown in Fig. 1.

![Fig. 1. Compressive stress profiles produced by the combinations of heat treatment and shot peening given in Table 2.](image)

RESULTS

The S-N curves for the specimens tested in plain fatigue are shown in Fig. 2 and those tested in fretting-fatigue are shown in Fig. 3. To show the effects of peening, certain of the curves are replotted in Fig. 4 for specimens given the normal single stage ageing.
Fig. 2. S-N curves in plain fatigue.

Fig. 3. S-N curves in fretting-fatigue.
To shorten the description the following terminology has been used for the various treatments:

0 = unpeened
1A = peened after single stage ageing
1B = peened in SHT in single stage ageing
2A = peened after two stage ageing
2B = peened between the two stages in two stage ageing

(a) Plain fatigue

In high cycle fatigue the material in condition 0, 1B, 2A and 2B all have the same fatigue strength at $10^7$ cycles, namely 125 MPa, whereas those in condition 1A are somewhat higher at 154 MPa. In low cycle fatigue, i.e. at higher alternating stresses, further differences are seen. The materials ranked in order of increasing fatigue life are as follows: 2B, 0, 1B, 2A, 1A.

(b) Fretting fatigue

In high cycle fatigue conditions 0 and 2B give a fatigue strength at $10^7$ cycles of 91 MPa, conditions 1B and 2A 125 MPa, and 1A 155 MPa. In low cycle fatigue the ranking in order of increasing fatigue lives is 0 = 2B, 1B, 2A and 1A, i.e. very similar to the ranking in plain fatigue.

From these results it is obvious that shot-peening after single stage ageing produces the best fatigue behaviour. In Fig. 4 the fatigue and fretting fatigue curves for the alloy in this condition are compared where...
it can be seen that the two curves are coincident; in other words, the material is insensitive to fretting. The other two curves compare the performance in the unpeened condition, where it is seen that fretting produces a lower fatigue strength.

MICROSCOPE EXAMINATION

Certain of the specimens were examined before and after testing by optical and scanning electron microscopy. Fig. 5 is an SEM picture of the shot-peened surface of a specimen in the 1A condition, and Fig. 6 is an optical micrograph of a section through the surface. The dimples caused by the shot can be clearly seen. Fig. 7 is a SEM picture of the

Fig. 5. SEM picture of shot-peened surface, shot-peened after single stage ageing.

Fig. 6. Optical micrograph of cross-section through surface shown in Fig. 5. X70.
shot-peened surface of a specimen in the 1B condition. The dimples are larger and evidence of folding of the surface of the material can be seen. This is further visible in the section in Fig. 8. Certain of the specimens were carefully polished to remove the surface roughness without interfering with the peening damage at the base of the dimples.

Fig. 7. SEM picture of shot-peened surface, shot-peened in SHT condition and then aged.

Fig. 8. Optical micrograph of cross-section through surface shown in Fig. 7. X70.

Fig. 9 is an optical micrograph of such a specimen in the 1B condition. Crack-like folds can be seen radiating from the damaged area.

Fig. 10 is an optical micrograph of the polished surface of a specimen
in the 1B condition after testing in fatigue. Fatigue cracks can be seen emanating from a region of peening damage. Fig. 11 is a SEM picture of another part of the surface and shows a fatigue crack spreading from peening damage which is clearly seen as surface folding. Finally, Fig. 12 is an optical micrograph of the polished surface of a fretted specimen. Parallel cracks can be seen which have been initiated by the fretting action rather than peening damage.

Fig. 9. Optical micrograph of surface shot-peened in SHT and then aged X70.

Fig. 10. Optical micrograph of surface shot-peened in SHT and then aged, after testing in fatigue X70.
DISCUSSION

Comparison of the stress distribution curves in Fig. 1 with the fatigue curves in Fig. 2 shows that the reduction in the compressive stress caused by the 1B and 2B treatments has led to a reduction in fatigue strength; in the case of the 2B treatment to a level lower than the unpeened material. Furthermore, the evidence from the microscope examination is that the surface and subsurface damage caused by shot-peening in the solution heat treated condition (1B) introduces surface
defects and cracks from which a fatigue crack can readily propagate.

In fretting the observation is similar, although in this case there is no evidence to suggest that the surface damage due to the shot-peening has contributed to failure. The fretting itself is a very efficient initiator of fatigue cracks as Fig. 12 clearly shows. The fretting fatigue cracks then appear to grow quite independently of the peening damage in the surface of the specimen.

If the fatigue and fretting fatigue curves are compared for the 7075 alloy peened in the SHT condition and then aged (1B) it can be seen that, like the 2014A alloy (3), the alloy in this condition is insensitive to fretting damage. However, in this 7075 alloy the level of fatigue properties is only a little above that of the unpeened material, and this is almost certainly due to a combination of surface damage introduced by peening (e.g. see fig. 8) and loss of compressive peening stresses. The loss of compressive stress will take place partly during the final age (after peening) and partly due to fading during fatigue. The 7075 alloy therefore appears to be much less resistant to fading than the 2014A reported earlier (3). The reason for this is probably due to the different nature of the precipitates that form on the dislocations introduced into the surface by the peening operation. In the case of 2014A alloy these precipitates will be the transition phase S'(Al2CuMg) and they appear to effectively pin the dislocations, prevent their rearrangement during heat treatment and fatigue testing and so produce a surface that retains its residual compressive stress. In the case of 7075 alloy, the precipitates that form on the dislocations are the transition phase η'(MgZn2) and this appears to be unable to prevent dislocation rearrangement during ageing/fatigue testing and so the surface loses most of its compressive stresses and hence the fatigue properties are only marginally improved.

The best fatigue and fretting fatigue properties are produced in 7075 by peening after the final age, and again in this condition the alloy appears to be insensitive to fretting damage. Multiple cracking of the shot-peened surface occurs as a result of fretting (see fig. 12) but the cracks do not propagate due to the presence of the compressive stresses. Thus it does not matter whether the alloy is subjected to fatigue or fretting fatigue, in either case a fatigue crack has to be slowly propagated through the region of compressive stress and once away from the immediate point of fretting contact, this process will be the same for both fatigue and fretting fatigue.

SUMMARY

1. Shot peening 7075 alloy between solution heat treatment and ageing or after final ageing, produces a material that is insensitive to fretting.

2. The heat fatigue/fretting fatigue properties are produced by peening after the final age.

3. Peening after solution heat treatment but before ageing only marginally improves the fatigue properties and it does not produce a surface microstructure that is resistant to stress fading during fatigue. It therefore behaves in a manner quite different from 2014A alloy indicating that η'(MgZn2) precipitates are not as effective at pinning dislocations as are S'(Al2CuMg) precipitates.
REFERENCES

