THE FATIGUE OF AN ALUMINIUM ALLOY PRODUCED BY FRETTING ON A SHOT PEENED SURFACE

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ABSTRACT

An Al-4.2%Cu-0.7%Mg-0.7%Si age hardening alloy (2014A) has been shot peened and subjected to plain and fretting fatigue. The shot peening improves both plain and fretting fatigue strengths, and in particular the fretting fatigue strength of the alloy in the fully aged condition is increased by 130%. The improvement in fretting fatigue properties is largely due to the residual compressive stresses induced into the surface by the shot peening process. Surface roughening also has a small beneficial effect but work hardening of the surface does not influence the fretting fatigue properties.

KEYWORDS

Fatigue, fretting fatigue, shot peening, aluminium alloy.

INTRODUCTION

Shot peening involves the bombardment of the specimen by a stream of steel shot, a process that results in localised plastic flow at the surface. The localised plastic flow causes work hardening of the surface, the generation of a compressive residual stress, and general roughening of the surface. All of these processes can be expected to affect both the plain and fretting fatigue properties of an alloy. Furthermore, the magnitude of their effect will depend on the state of heat treatment of the alloy. For example, it is known that harder materials are more resistant to fretting wear damage, whereas in fretting fatigue, cast or annealed materials are less sensitive to fretting than materials which are work hardened or age hardened because of the latter's increased notch-sensitivity. In plain fatigue, fatigue strength is related to ultimate tensile strength, but under fretting conditions this is not so. Many materials of widely different tensile strengths display a very similar fretting fatigue strength of about 150 MPa at 10^7 cycles (Waterhouse, 1981).

Surface roughness is generally detrimental in plain fatigue but in fretting fatigue it may be beneficial. Bramhall (1973) has shown that limiting the size of the areas of real contact in a larger area of apparent contact produces a much improved fretting fatigue performance with a doubling of the fretting fatigue strength.

The object of the present paper is to assess the relative contribution that work hardening, residual compressive stress and general surface roughening can make to the fretting fatigue properties of an age hardened alloy that has been heat treated to three different states of precipitation followed by shot peening.

EXPERIMENTAL

The work described in the present paper has been carried out entirely on the aluminium alloy 2014A which had a composition (wt.%) of Al-4.2%Cu-0.7%Mg-0.7%Si. The alloy was solution treated at 505°C and given three standard ageing treatments:

(a) Aged 5 h at 185°C (TF temper)
(b) Aged 48 h at 20°C (TB temper)
(c) Aged 2 h at 400°C and furnace cooled (fully annealed).

Cylindrical specimens 9.5 mm diameter were produced from the alloys with parallel flats forming the gauge length. Fretting was induced into the specimens by clamping a pair of bridges of the same material and heat treatment onto the parallel flats, and then subjecting the specimen to rotating-bending at 50 Hz on a four-point-loading fatigue machine. Testing was done using fatigue stresses in the range 60-350 MPa, but the clamping stress on the bridges was maintained constant at 32 MPa.

Some specimens have been tested in the aged condition without further treatment; others have been subjected to shot peening after ageing. The shot size was 0.84 mm and peening was carried out to an intensity that produced an arc height of 0.30-0.40 mm on a standard Almen A test strip (dimensions 76 mm length x 19 mm width x 1.3 mm thickness). Samples were tested in both the as-peened condition, and after polishing off the surface dimples produced by the peening process.

Shot peening produces appreciable compressive stresses in the peened surface and the magnitude of this stress has been measured by the double exposure X-ray diffraction method employing CuK_α radiation. The distribution of these stresses below the surface has been investigated by progressively etching away the surface with sodium hydroxide solution.

Finally, the hardening of the surface produced by shot peening was measured by taking sections through the samples and performing microhardness traverses.

Nature of the Shot Peened Surface

The shot peening process severely deforms the surface layers, resulting in roughening and, in some cases, surface cracking. Since these effects can have a significant influence on fatigue and fretting-fatigue properties it is important to characterise the shot peened surface.

Scanning electron microscopy of the peened surface (fig. 1) shows characteristic dimpling, the crater size being approximately 200 µm diameter. The roughness of the shot peened surface was determined by drawing a very fine diamond stylus across the surface and measuring the vertical movement of the stylus (fig. 2). From these measurements the centre line average (R_a) was calculated for ten different specimens. A value of R_a = 6.6 µm was obtained for the shot peened material compared to a value of 0.13 µm for unpeened specimens.

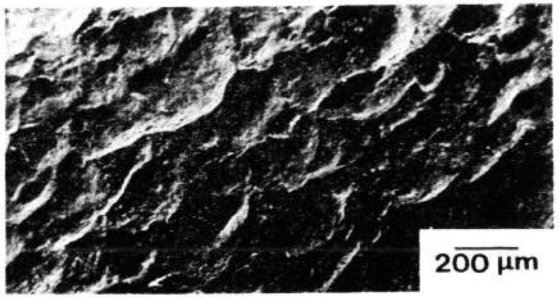

Fig. 1 Scanning electron micrograph of the peened surface

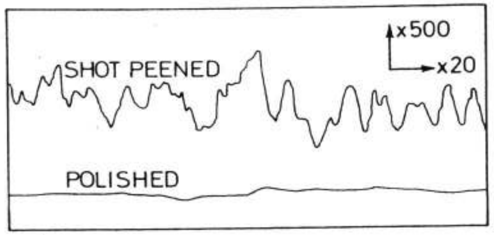

Fig. 2 Surface profile measurements

Examination of the peened surface at higher magnification revealed some surface cracking (fig. 3) and also evidence that during bombardment parts of the surface had been folded back over themselves, producing thin lamella regions (fig. 4).

Plain Fatigue Characteristics

S-N curves for the alloy in the fully aged condition are given in fig. 5, where it can be deduced that the plain fatigue strength at 10^7 cycles is improved by 50% due to shot peening. Polishing the surface to eliminate the craters produced by the peening operation produced a further, but very small, improvement.

Fretting Fatigue Characteristics

S-N curves for the alloy in the fully aged condition are given in fig. 6 and from these curves it is clear that the improvement in fretting fatigue strength due to peening is much higher than was the case for plain fatigue.

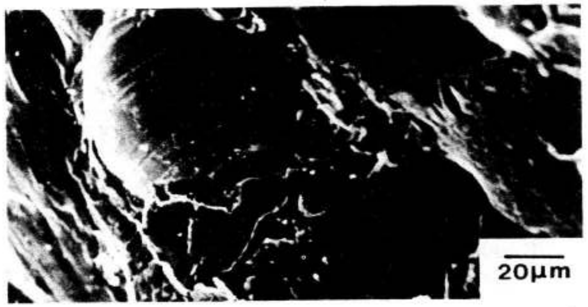

Fig. 3 Surface microcracks in the shot peened surface.

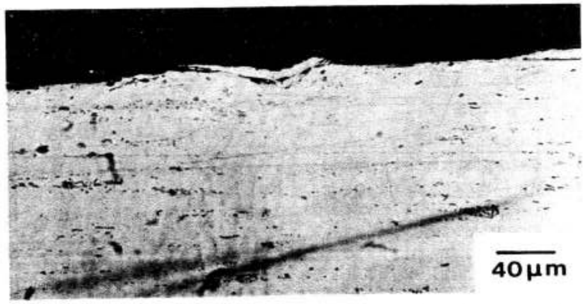

Fig. 4 Section through a shot peened surface showing surface folding.

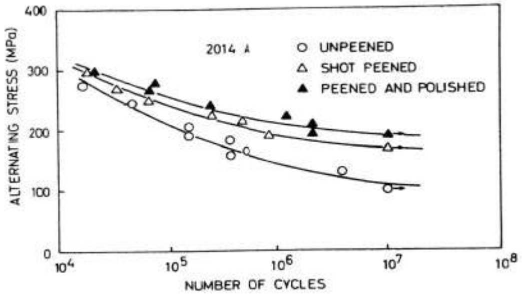

Fig. 5 S-N data for plain fatigue tests on fully aged alloys. Test temperature 20°C. Test frequency 50 Hz.

At 10^7 cycles the fretting fatigue properties have been increased by 130%. Polishing to remove the surface craters did not produce any further improvement in fatigue resistance, in fact the fretting fatigue properties were reduced by such a smoothing operation.

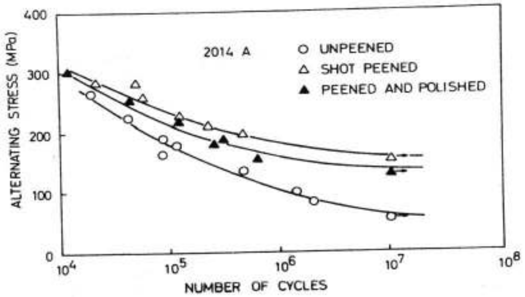

Fig. 6 S-N data for fretting fatigue tests on fully aged alloys. Test temperature 20°C. Test frequency 50 Hz.

Relative Effects of Surface Hardening and Surface Stresses

Surface roughening appears to have a small beneficial effect on fretting fatigue properties but the major improvement to fretting fatigue produced by shot peening will be caused either by work hardening of the surface layers or residual compressive stresses induced into the surface. Microhardness traverses on sections through the peened surface showed the hardness to be increased by peening from 125 to 250 VPN and that significant hardening existed to a depth of 0.5 mm. Stress measurement by X-ray diffraction showed the surface to have a compressive stress of 250 MPa. The distribution of stress below the surface was determined by progressively removing the surface layers and carrying out X-ray measurements on the freshly exposed surface. The stress, when corrected for the relief of stresses caused by the removal of surface layers, was found to decrease with increasing distance from the surface and became tensile at a depth of 0.6 mm.

To assess the separate effects of work hardening and compressive stress at the surface of the shot peened material, a series of peened samples were prepared with the surface stress removed and then subjected to fretting fatigue tests. Removal of the stress without significantly affecting the surface hardness was achieved by stretching the samples after shot peening. Residual stress measurement after stretching showed that at least 75% of the compressive stress had been removed by this treatment. Fretting fatigue results on the stretched specimens are given in fig. 8 where it can be seen that the fatigue properties have been reduced to the same level as the unpeened material. It can be concluded that work hardening of the surface by the peening is having little or no effect on the fretting fatigue strength.

Metallography of Fretting Fatigue Crack Propagation

Crack initiation in non-peened material was always at the edge of the fretting scar region, and multiple cracking was commonly observed. The initial direction of the crack was always at a fairly steep angle to the surface, i.e. inclined at angles between 50° and 80° to the surface (fig. 8).

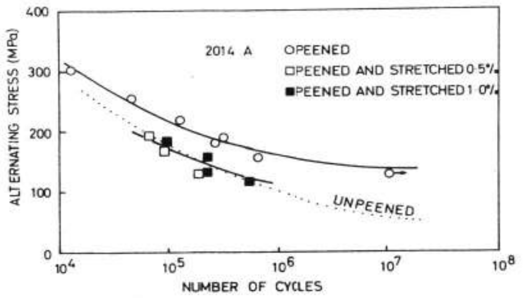

Fig. 7 Fretting fatigue curves for fully aged alloys.
Test temperature 20°C. Test frequency 50 Hz.

Crack initiation in peened material was again at the edge of the fretting scar region, but the initial direction of the crack followed a much shallower angle to the surface, the angle of inclination being somewhere between 15° and 35° to the surface (fig. 9). The shallow angle of crack propagation in shot peened material is a direct consequence of the residual compressive stress that exists in the surface. This will have the effect of moving the principal tensile stress in the surface layers to a direction more nearly normal to the surface. A shallow angle of crack propagation then results since the fatigue crack will always propagate in a direction perpendicular to the principal tensile stress.

In both the unpeened and peened material once the crack had moved out of the zone influenced by the fretting stresses, the direction of cracking was always at 90° to the surface, i.e. perpendicular to the axial fatigue stress.

DISCUSSION

Shot peening a metallic surface produced surface roughening, work hardening and residual compressive stresses. For 2014A aluminium alloy work hardening has no effect on the fretting fatigue properties, surface roughening produces a small improvement, leaving residual compressive stresses to produce the major contribution to the fretting fatigue properties of shot peened material. The action of the compressive stress will be to close-up cracks at the surface and prevent their propagation. Furthermore the compressive stress will reduce the effective tensile stresses induced by the fretting action at the specimen surface and this will have the effect of delaying or preventing crack initiation.

The action of surface roughening producing a small improvement in fretting-fatigue properties was unexpected. With such a rough surface, contact between specimen and the bridge feet will be at the tops of rather pronounced asperities. There is then the possibility that these asperities will deflect elastically under the fretting action, and thus take up the relative movement (slip) between the surfaces. Without such relative movement fretting damage will be greatly reduced. Furthermore, it is likely that the craters in the specimen surface act as reservoirs for fretting debris which is then prevented from causing further abrasive damage of the specimen surface.

Fig. 8 Section through a fretted region of a non-peened alloy

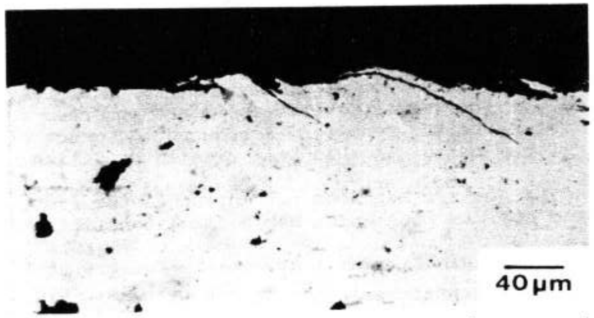

Fig. 9 Section through a fretted region of a peened alloy

The effects of shot peening on plain fatigue and fretting fatigue strengths at 10^7 cycles are summarised in table 1 for alloys in various heat-treated conditions.

TABLE 1 Plain Fatigue and Fretting Fatigue Strengths at 10^7 Cycles

Heat treatment	% reduction in fatigue strength due to fretting	% increase in plain fatigue strength due to shot peening	% increase in fretting fatigue strength due to shot peening
fully aged	45	65	130
naturally aged	20	45	50
annealed	20	25	20

For plain fatigue the improvement in fatigue strength produced by shot peening increases in the order : annealed → naturally aged → fully aged. The major effect producing the improvement in fatigue properties is the compressive stress at the surface, and the magnitude of this stress is approximately three quarters of the yield stress for the peening conditions used in the present work. Since the yield stress increases as we move from annealed, to naturally aged, to fully aged, it follows that the compressive stress at the surface is increasing along the same sequence and this therefore accounts for the relative improvements in the fatigue properties in the three heat-treated conditions.

A similar trend is apparent for the improvement in fretting fatigue properties by shot peening, with a very large improvement being shown for the alloy in the fully aged condition. A possible explanation for the large improvement in the fully aged alloy is a reduced incidence of surface cracking and folding when the alloy is in this condition. For alloy in the annealed and naturally aged conditions the surface is softer and therefore more likely to suffer damage from overpeening. The resulting microcracks and folds in the surface as well as providing fatigue sites will also reduce the compressive stress in the surface and thus make fretting-fatigue crack propagation easier.

CONCLUSIONS

1. Shot peening improves the plain fatigue strength of 2014A aluminium alloy by 25-65%, the effect increasing for alloy in the annealed → naturally aged → fully aged conditions.
2. Shot peening improves the fretting fatigue strength of 2014A aluminium alloy by 20-130%. The largest improvements are observed for fully aged alloys and this may be the result of a reduced incidence of surface microcracking for material in this heat treated condition.
3. Work hardening of the surface does not influence the fretting fatigue properties, and surface roughening has a small beneficial effect.
4. The improvement of plain fatigue and fretting fatigue strengths in 2014A aluminium alloy is largely due to the residual compressive stresses induced into the surface by the shot peening process.

ACKNOWLEDGEMENTS

The authors would like to thank the Procurement Executive, Ministry of Defence for financial support, and P.J.E. Forsyth, C.J. Peel and B. Evans for helpful discussions.

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