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Effect of Vapour Blasting on Fatigue Life of an Age-Hardened Aluminium Alloy

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In addition to being used by industry as a means of surface cleaning and of imparting a matt finish for subsequent operations, vapour blasting has also been used as a means to improve the fatigue life of parts made of aluminium alloys. The present work investigates the effect of vapour blasting on the fatigue life of age-hardened aluminium alloys, using 6063 aluminium alloy as a model material. It is shown that vapour blasting not only produces a hardened surface layer but also roughens the surface of the material. This, in turn, produces an intricate effect on the fatigue life of the material. At low blasting pressures, both the surface hardness and the depth of hardening increase significantly while the surface roughness degrades only moderately with blasting pressure. This gives rise to an increase in fatigue life. On further increasing the blasting pressure, however, while the rate of surface hardening gradually saturates, there is an abrupt increase in the surface roughness due to severe cuts and deep indentations produced by the high velocity abrasive. This causes the fatigue life of the material to decrease at high blasting pressures. The present work shows that there exists an optimum blasting pressure beyond which the fatigue life of age-hardened aluminium alloys degrades with a further increase in blasting pressure.

1. INTRODUCTION

Grit blasting has been commonly used in industry as a means of surface cleaning and for imparting a roughened, matt finish on parts made of aluminium alloys for subsequent painting or coating operation [1]. The grit particles can either be applied dry or in slurry form. The latter is more commonly referred to as vapour or wet blasting, during which fine abrasives, such as alumina or quartz particles, are propelled onto the metal surface to be treated in a stream of water. The technique has also been applied by industry to improve the fatigue life of aerospace components made of aluminium alloys.

Unlike shot peening, which uses rounded metal shot, grit blasting uses hard, angular abrasives which tend to cut the metal surface. In addition, a comparatively low impingment energy is used in grit blasting. Although shot peening has been extensively investigated by researchers [2,3], only limited works have so far been reported on the effect of grit blasting on the fatigue life of metals and alloys.

Working with sand blasting of 1010 steel, Badawi and co-workers [4] reported a residual compressive stress state which presisted to a depth of a few hundred microns below the blasted surface. The magnitude of the residual compressive stress was found to increase with decreasing grit size of the sand used but was only lightly influenced by the blasting angle and distance. They also found that in the case of blasting treatments, micro-hardness measurement provided a fair indication of the distribution of residual stresses in the surface layer. Close correlation was also noted between the surface roughness and the magnitude of residual stresses produced.

This work studies the effect of vapour blasting on the surface texture and hardening characteristics and resultant fatigue life of 6063 aluminium alloy. The magnitude and distribution of residual stresses

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produced by the blasting treatment are not investigated here due to the lack of facilities for such measurements.

2. EXPERIMENTAL

2.1. Material and Test Specimen

The material used was 6063 aluminium alloy the composition of which is given in Table 1. The as-received bar stock, 19 mm in diameter, was given a solution anneal at 520°C for 1 h. After annealing, they were cold extruded to 16 mm in diameter, straightened by means of a hydraulic press, and then machined into fatigue test specimens shown in Fig. 1. After machining, the specimens were again solution treated at 520 °C for 1.75 h, followed by water quenching, producing an average linear intercept grain size of about 36 μm. The fine grain size was chosen to simulate that of age hardenable aerospace aluminium alloys. All the specimens were further artificially aged at 175°C for 8 h, giving a peak hardness of about 40.7 HB. After ageing, the specimen gauge sections were polished manually using 1000 grit emery paper along the specimen axis, to remove the scratches caused by machining and poor handling. At this stage, the specimen was ready for the vapour blasting treatment.

Table 1: Nominal composition of 6063 aluminium alloy (wt%)

Al	Si	Fe	Mg	Mn	Cr	Zn	Ti	Cu
98.1	0.4	0.35	0.7	0.05	0.1	0.1	0.1	0.1

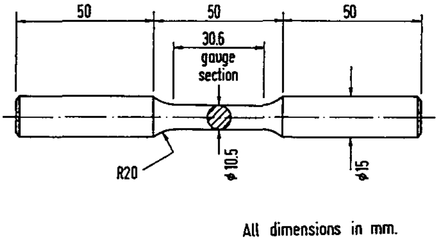

Figure 1. Dimensions of the fatigue specimen.

2.2. Blasting Conditions

Vapour blasting with slurry of aluminium oxide suspended in water was used in the present work. The aluminium oxide particles had a 90-100 grit size, and were angular in shape with sharp edges.

Only the effect of blasting pressure was investigated; they were varied from 20 to 90 psi (0.14 to 0.62 MPa). The nozzle-to-specimen distance was fixed at about 6 in. (152 mm). The blasting was carried out at normal impingement by holding the nozzle at right angle to the specimen axis while rotating the specimen manually during blasting. The entire specimen gauge section including the fillets was blasted until an even surface texture was obtained.

2.3. Surface Roughness Measurement

The surface roughness of the artificially aged and the vapour blasted specimens was taken with a Surtronic 3 tester. The parameter recorded was R_a which is the average deviation from the mean surface height. It was set to 9.99 μm with a cut-off length of 0.8 mm. The specimens were cleaned in an ultrasonic cleaner before the measurement to remove any debris trapped accidentally on the blasted surface. A total of six measurements were taken along the gauge length of each specimen.

After the measurements, the specimen surfaces were examined in the scanning electron microscope to study the various surface features produced by the vapour blasting treatment.

2.4 Micro-Hardness Measurement

The micro-hardness values were determined at 100g load as a function of depth from the blasted surface. Electro-polishing was used to expose the subsurface material for the measurements. The polishing solution used was 6 ml $HClO_4$/14 ml H_2O/80 ml C_2H_5OH. The polishing was carried out at 17 V, to remove about 5 to 10 μm thick material each time. A total of six measurements were taken along the polished length of the specimens, at an interval of about 0.2 mm. This was continued until the exposed material registered a micro-hardness value comparable to that of the bulk material.

2.5 Fatigue Tests

All specimens were tested in rotary fatigue under four point bending conditions at 50 Hz at room temperature. Since the fatigue machine used was fairly old, to limit machine vibration, the fatigue tests were carried out at constant deflections which, in turn, were determined by pre-set initial loads and hence surface stresses. This was achieved via the following procedure.

With the knowledge of the specimen and loading geometries, the load required to generate the desired surface stress, calculated using the formula given in the machine manual, was applied onto the specimen via the load chain. This caused the specimen to deflect downward accordingly. Two hard rubber pads were then inserted beneath the specimen grips, gently lifting the specimen up until it again became about level. Then, an additional load was applied onto the load chain to bring the deflection to the previously registered value. This additional load also acted as the clamping load to fix the specimen and the grips in position. In what follows, for the ease of description and result presentation, only the pre-set initial surface stress values will be quoted.

Using the above technique, the artificially aged specimens were fatigued to fracture under various initial surface stresses to establish the S-N curve. This was done to determine the initial load and hence surface stress level required to produce a fatigue life of about 10^5 cycles.

The vapour blasted specimens were similarly tested to fracture at a pre-set initial surface stress which produced an average fatigue life of about 5×10^5 cycles for the artificially aged material. As will be shown later in Section 3.2, the present method of pre-setting the initial surface stress while clamping the specimen resulted in an appreciable amount of scatter in the fatigue lives obtained. This was because all the specimens after the vapour blasting treatment were slightly warped. They either curved upwards or downwards during initial mounting. Upon switching on the fatigue machine, the specimen would tend to self-align but was unable to do so because of the constraint imposed by clamping. In so doing, the specimen would take up part of the clamping load if it initially curved downwards hence actually experiencing a higher surface stress. On the other hand, it would shed part of the applied load if it initially curved upwards hence actually experiencing a smaller surface stress. To aid result interpretation, the shift in the specimen deflection before and after the fatigue machine was switched on was monitored by means of two dial gauges placed at the specimen grips. It should be noted that a positive (or downward) shift in deflection detected by the above means would indicate that the actual deflection hence surface stress experienced by the specimen must be smaller than the pre-set value, while a negative (or upward) shift would indicate otherwise. Furthermore, the larger the shift in the specimen deflection detected, the larger is the deviation of the actual surface stress from the pre-set value.

3. RESULTS

3.1. Fatigue Life of As-Hardened Material

Fig. 2 shows the fatigue lives of artificially aged 6063 aluminium alloy against the initial surface stress obtained under the present test conditions. The data show an appreciable amount of scatter at low stresses. To reduce the amount of scatter while keeping the surface stress low to simulate the condition experienced by most aerospace components, a surface stress level of 112 MPa, which produced an average fatigue life of about 5×10^5 cycles, was selected for the subsequent study on the effect of blasting pressure.

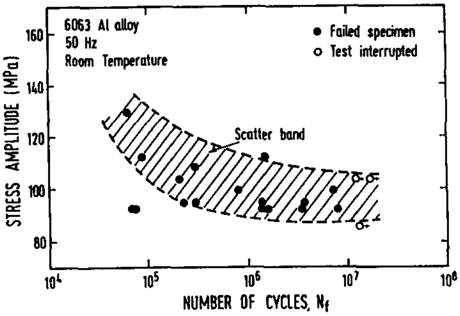

Figure 2. Fatigue life as a function of surface stress for 6063 aluminium alloy aged to peak hardness.

3.2. Fatigue Life of Vapour Blasted Specimens

The effect of blasting pressure on the fatigue life of 6063 aluminium alloy at a `surface stress of 112 MPa', set using the present loading procedure, is shown in Fig. 3. The fatigue life for the artificially aged material (which corresponds to zero blasting pressure) is also indicated in the same figure. Also indicated next to each data point is the amount of shift in the specimen deflection registered before and after the fatigue machine was switched on. A positive value indicates a downward shift while a negative value indicates an upward shift.

The results show a tremendous amount of scatter, namely, the fatigue lives differ by up to three orders of magnitude for a given blasting pressure. This strongly indicates that the actual stresses experienced by the specimens could be very different from the pre-set value of 112 MPa. On closer examination, it can be seen that for a given blasting pressure, the fatigue lives of those specimens for which the shift in specimen deflection is positive (i.e. downward shift) are always higher than those for which the shift is negative (i.e. upward shift). Furthermore, the fatigue life increases as the shift in specimen deflection becomes more positive (or less negative). As explained in Section 2.5, a positive shift in specimen deflection would result in lower surface stresses while a negative shift in higher surface stresses than the pre-set value of 112 MPa. In other words, the actual lives of blasted specimens at 112 MPa should be those which give a zero shift in specimen deflection when the fatigue machine is switched on. The above reasoning enables us to deduce the fatigue lives of the blasted specimens at an applied surface stress of 112 MPa, which are given by the shaded band in Fig. 3.

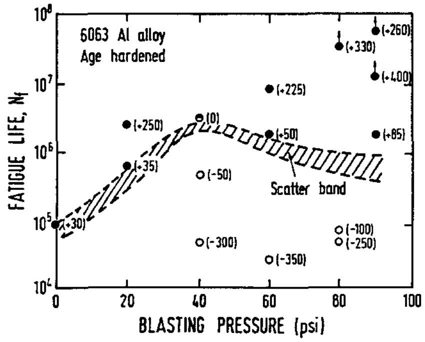

Figure 3. Fatigue life as a function of blasting pressure. The numbers next to the data points indicate the amount of shift in specimen deflection before and after the fatigue machine was switched on (positive for downward shift and negative for upward shift). The shaded band is the deduced lives at a surface stress of 112 MPa.

The shaded band in Fig. 3 shows that vapour blasting can influence the fatigue life of age-hardened 6063 aluminium alloy in an intricate manner. The fatigue life first increases with increasing blasting pressure, reaching a maximum at about 40 psi. Beyond 40 psi, however, the fatigue life decreases with a further increase in blasting pressure. It is also interesting to note from Fig. 3 that the improvement in fatigue life at the optimum blasting pressure of 40 psi is quite substantial, being about 30 times that of the artificially aged but unblasted material.

3.3. Surface Texture and Roughness

The surface roughness of the artificially aged and vapour blasted specimens are plotted in Fig. 4 against the blasting pressure. The error bars show the range of the R_a values for the nine measurements taken on each specimen. Fig. 4

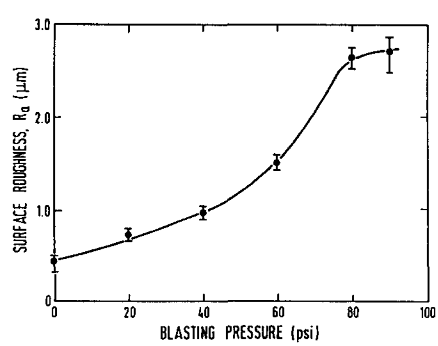

Figure 4. Surface roughness as a function of blasting pressure.

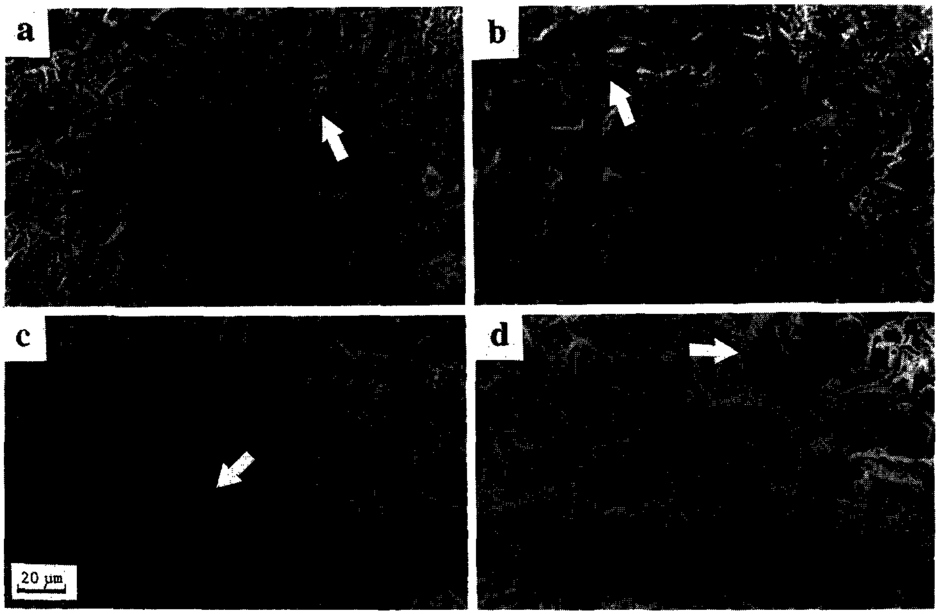

Figure 5. Surface textures produced by vapour blasting at increasing blasting pressure. (a) 20 psi, (b) 40 psi, (c) 60 psi and (d) 80 psi. The arrows in (a), (b), (c) and (d) indicate deformed patches, shallow cuts, indentation pits and deep cuts respectively.

shows that beyond 40 psi, the surface finish of the blasted surfaces starts to degrade rapidly and even more so after 60 psi.

Before vapour blasting, the specimen surface was relatively smooth except fine polishing lines which run at small angles to the specimen axis. Fig. 5 shows the surface appearances produced by vapour blasting. Four main features on the blasted surfaces are identifiable: (i) deformed patches which are relatively flat and featureless, (ii) cuts which are comparatively thin and shallow, (iii) cuts which are broad and deep and are often decorated with plough-out features, and (iv) deep indentations that appear as dark pits. By and large, deformed patches and shallow cuts are common features at low blasting pressures, Figs. 5(a) and (b). With increasing blasting pressure, both the density of deep cuts and the size of indentations increase accordingly, Figs. 5(c) and (d).

Both Figs. 4 and 5 collectively show that the resultant surface roughness depends strongly on the type and density of surface defects produced by vapour blasting. At low blasting pressures, deformed patches and shallow cuts are dominant surface features and the roughness of the resultant surfaces degrades gradually with blasting pressure. Above 60 psi, however, deep cuts and indentations become more and more prominent, causing the surface roughness to degrade appreciably.

3.4. Micro-Hardness Measurement

Fig. 6 shows the micro-hardness of the vapour blasted specimens as a function of depth from the surface. In all cases, the hardness value is maximum at the surface of the blasted specimens. These surface hardness values are plotted against the blasting pressure in Fig. 7. The hardness values for specimens blasted at 80 and 90 psi are not

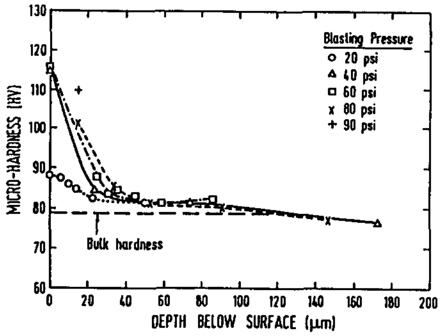

Figure 6. Micro-hardness profiles produced by the vapour blasting treatments.

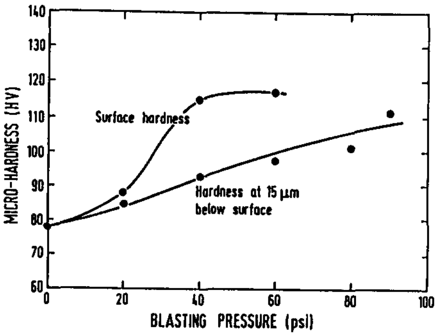

Figure 7. Surface and sub-surface hardening characteristics as a function of blasting pressure. The sub-surface hardness values are extracted from Fig. 6.

included in this figure due to the inaccuracy in the hardness readings as a result of the very rough surfaces produced by the high energy particles. For this reason, the hardness values at a depth of 15 μm from the surface of the blasted specimens, extracted from the curves in Fig. 6, are also given in Fig. 7. An abrupt increase in surface hardness is most evident over the blasting pressure range from 20 to 40 psi.

Fig. 8 shows the depth of the hardened surface layer, defined as the depth from the surface at which the hardness drops to about the bulk value. This figure shows that in general, the depth of hardening increases with increasing blasting pressure. It should also be noted that a sharp increase in the depth of hardening occurs over the blasting pressure range from zero to about 40 psi.

4. DISCUSSION

As shown in Fig. 3, vapour blasting can affect the fatigue life of age-hardened 6063 aluminium alloy in a complex manner. At low blasting pressures, the fatigue life improves with increasing pressure. A maximum in fatigue life is noted at a pressure level of about 40 psi, beyond which the fatigue life decreases with a further increase in blasting pressure.

The present results also show that vapour blasting not only roughens but also work-hardens the surface of the material. Rough surfaces generally exhibit inferior fatigue properties due to the stress-raiser effect produced by the surface defects. On the other hand, the effect of work-hardening introduced during vapour blasting would lead to an increase in fatigue life. It is possible that the dislocation substructure generated by vapour blasting at the surface or sub-surface layer would produce a hindering effect on the formation of persistent slip bands thereby delaying fatigue crack nucleation [5]. Furthermore, vapour blasting also generates compressive residual stresses in the

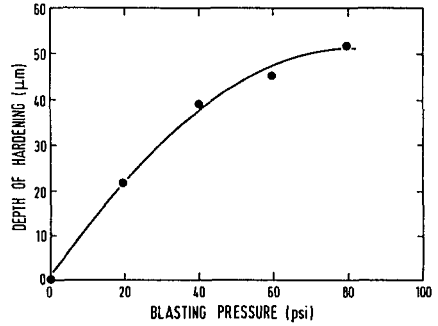

Figure 8. Depth of hardening as a function of blasting pressure.

surface layer. Such a state of compressive residual stress is beneficial in fatigue in that it helps to retard both the nucleation and growth of fatigue cracks. In this work, we were unable to measure the residual stress produced by the blasting treatment due to the lack of facilities for such measurements. However, the works of Badawi and co-workers [4] showed that there exists a close correlation between the residual stress and the micro-hardness depthwise across the surface of sand blasted 1010 steel specimens in that the higher the micro-hardness value the higher is the magnitude of the compressive residual stress. The micro-hardness measurements provided in Figs. 6 to 8 may thus be used to provide an indication of the distribution pattern of the compressive residual stress in the surface layer at different blasting pressures.

The observed effect of blasting pressure on fatigue life of 6063 aluminium alloy can be understood from the relative magnitudes of the various competing effects described above produced by the blasting condition concerned. As can be seen from Figs. 4, 7 and 8, the initial increase in fatigue life with blasting pressure of up to 40 psi can be attributed to the sharp increase in surface hardness and the depth of hardening but a much gentle increase in the surface roughness with increasing blasting pressure. Therefore, in this pressure range, the benefical effects of surface work-hardening and the resultant residual compressive stresses have outweighed the detrimental effect of a slightly rougher surface produced by the vapour blasting treatment, resulting in an improvement in the fatigue life.

Beyond 40 psi, the rate of increase in surface hardness with increasing blasting pressure becomes less pronounced. In contrast, there is an abrupt increase in the surface roughness over the blasting pressure range from 40 psi to 80 psi. It is thus probable that from 40 psi onwards, the surface roughness effects would become dominant. A very rough surface containing many stress raisers is expected to aid fatigue crack nucleation, thereby lowering the overall fatigue life of the material.

5. CONCLUSIONS

1. At low blasting pressures, the surface defects produced are deformed patches and shallow cuts, which cause the surface roughness of the specimen to increase gradually with increasing blasting pressure. At high blasting pressures, however, deep cuts and indentations become more and more prominent, resulting in an abrupt increase in the surface roughness on further increasing the blasting pressure.
2. An optimum blasting pressure exists beyond which the fatigue life of vapour blasted specimens decreases with further increase in blasting pressure. For 6063 aluminium alloy aged to peak hardness under the blasting condition used in the present work, the optimum blasting pressure was found to be about 40 psi.
3. The increase in the fatigue life at low blasting pressures is a result of the sharp increase in surface hardness and depth of hardening as opposed to the slight increase in the surface roughness produced by the low velocity abrasive.
4. The decrease in fatigue life at high blasting pressures is a result of the marked increase in surface roughness associated with the more extensive surface damages produced by the high velocity abrasive together with the saturation of the hardening effect at high blasting pressures.

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REFERENCES

1. S. Wernick and R. Pinner, The Surface Treatment and Finishing of Aluminium and its Alloys, 4th edition, Vol. 1, Robert Draper Ltd., Teddington, 1972, p.60.
2. A. Niku-Lari (ed.), Proceedings of the First International Conference on Shot Peening, Pergamon Press, Oxford, 1981.
3. Proceedings of the Second International conference on Shot Peening, The American Shot Peening Society, Chicago, 1984.
4. K. Badawi, J. Bielle, L. Castex and A. Giraudeau, in Advanced in Surface Treatments (edited by A. Niku-Lari), Vol. 3, Pergamon Press, Oxford, 1986, p.229.
5. M. Klesnil and P. Lukas, Fatigue of Metallic Materials (2nd revised edition), Elsevier, Amsterdam, 1992, p.70.