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The effect of heating shot peened sheets and thin plates of aluminium alloys

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2024, 7075 and 7475 aluminium alloy sheet and thin plate specimens shot peened to various intensities and subsequently exposed for periods up to 500 h at temperatures up to 120° C showed significant decreases in the level of residual stress induced by the shot peening and significant changes in geometrical contour even for exposure temperatures as low as 80° C. The higher the intensity of the shot peening, the higher the temperature of exposure and the longer the period of exposure, the greater was the relief of residual stress. After 40 h at 120° C the level of residual stress was reduced by more than 60%. Specimens formed to a given curvature by shot peening tended to straighten out on exposure at elevated temperatures. Such significant effects were obtained at temperatures as low as 80° C, these increasing with duration and temperature of exposure. The results and the possible effect of a tendency to change the contour of a flight component in service are discussed. Metallurgical ameliorative measures for some of these effects are demonstrated.

1. Introduction

Shot peening is used extensively to increase the resistance to fatigue and stress corrosion of components made from sheet or machined plate of high-strength aluminium alloys and intended especially for use in the aerospace industry. The process is also employed for the formation of parts made from sheets where complex, contours such as double curvature, are involved.

Occasionally such shot peened parts may be exposed, or may be considered for exposure, to elevated temperatures. Significant heating of external aircraft parts can result aerodynamically from flight at supersonic speeds and of internal parts from proximity to the engine. Relatively little, however, has been published on the effect of such exposure on the relief of the residual compressive stresses induced by the shot peening. Furthermore, nothing seems to have been published on the effect of such heating on the geometrical contours of the part. Both these effects are addressed in the present work. Without shot peening there are accepted upper limits to the temperatures at which aluminium alloys in their several heat-treatment tempers may be exposed [1].

2. Materials and methods

2.1. Materials

It is frequently the case that the main structural parts in aircraft are machined out of thick plate, the final thickness in certain regions being as little as 2 mm and elsewhere close to the original thickness. All the regions are shot peened to increase their fatigue strength. Accordingly, specimens to determine the effect of temperature on residual stress were machined from $1\frac{1}{2}$ in. (38.1 mm) thick 2024 and 7475 aluminium alloy plates in the T851 and T7351 tempers, respectively. These plates were supplied conforming to US Federal Specification QQ-A-250/4 and US Aerospace Material Specification 4202, respectively. Work was also carried out on initially clad sheet specimens of 2024 and non-clad sheet specimens of 7075 aluminium alloys in the T62 and T76 tempers, respectively. These sheets were of 4.5 and 4.0 mm thickness, respectively. They were supplied conforming to US Federal Specifications QQ-A-250/4 and QQ-A-250/12, respectively. In both cases the material was acquired in the annealed condition and was subsequently heat treated in-house to the T62 and T76 tempers, respectively, as per Israel Aircraft Industries Process Specification 01.9257. For the 2024 alloy, the cladding was removed chemically prior to heat treatment to the T62 temper. Maximum service temperatures recommended for the 2024 and 7475 aluminium plates and the 2024 and 7075 aluminium sheets used in this work are 177, 93, 177 and 121° C, respectively [1].

2.2. Methods

2.2.1. Shot peening practice

To determine the effect of exposure at elevated temperatures on the level of residual stress, specimens of dimensions 60 mm × 150 mm × 5 mm were machined from the 2024 and 7475 aluminium plates. These were saturation shot peened on one major side of the specimen with a visual coverage of 100% using cast steel balls of nominal size 550, Type 1A, Class 1 as per US Military Standard 851. Separate specimens were shot peened to intensities of 0.005A, 0.005C and 0.008C Almen, respectively. All these measurements are in inches. On the one Almen scale these values correspond to 0.005A, 0.0175A and

0.028A, respectively. Specimens to determine the effect of temperature on the shape of the part were cut from the 2024 and 7075 aluminium sheets and were of dimensions 130 mm × 380 mm. These were saturation shot peened on one side of the specimen with a visual coverage of 100%, using cast steel balls of size 230 to 280. Separate specimens were peened to intensities of 0.007A and 0.005C (0.0175A) Almen (henceforward 7A and 5C), respectively.

2.2.2. Exposure to elevated temperatures

The above shot peened specimens of plate origin were sectioned for the final X-ray diffraction examination to smaller, more convenient, specimens of size 15 mm × 20 mm. Such small specimens were exposed in an air furnace for periods up to 500 h at temperatures of 80, 95, 100 and 110° C and for up to 40 h at 120° C. Shot peened specimens for measurement of change of shape were exposed for periods up to 200 h at temperatures of 80 and 100° C and up to 70 h at 110 and 120° C. Two specimens were examined for every combination of intensity of shot peening and time and temperature of exposure for each alloy.

2.2.3. Measurement of residual stresses

Residual stresses were measured by the double-exposure X-ray diffraction technique using a flat plate camera and Cu$K\alpha$ X-radiation. Nickel powder of 99.95% purity, annealed at 500° C and thinly spread on the specimens for examination, was used for calibration purposes. Two specimens were examined for each combination of shot peening and exposure to temperature. Because the Debye–Scherrer diffraction rings were wide and thus could lead to inaccuracies in measurement of their width, 24 measurements were made on each ring to increase accuracy. All the residual stresses measured were compressive. Their accuracy is estimated to be between ±14 and ±35 MPa for the majority of the specimens and occasionally as much as ±70 MPa for specimens shot peened to maximum intensity where the resulting diffraction rings were broad and diffuse. Exposure of the shot peened specimens to the elevated temperatures employed in the present work had little effect on the sharpness of the diffraction rings. Shot peening results in a roughening of the surface of the specimen and therefore in a variable distance of this surface from the film on which the diffraction ring is recorded. This not only is an additional factor affecting the accuracy of the measurement of the residual stress but is a variable factor between specimens shot peened to different intensities [2]. For this reason all residual stresses measurements made after exposure of the specimens to elevated temperatures are given as a percentage of that measured prior to such exposure.

2.2.4. Measurement of change of shape

The sheet specimens became arced after shot peening as shown in Fig. 1. The extent of this elevation was measured at seven points along almost the full length, at mid-width, of the specimens after shot peening. The distortion of each specimen was symmetrical. Some typical results are shown in Fig. 2.

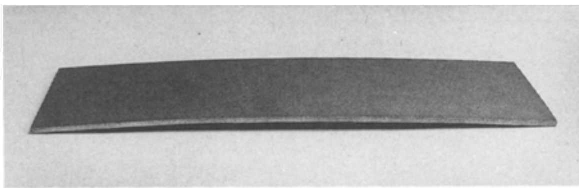

Figure 1 Typical arcing of a sheet specimen after shot peening.

The difference in height, h, between the ends of a central 360 mm length of the specimen and the peak of the arc, as measured on the convex surface, was taken as the extent of distortion. Eight specimens from each alloy were so measured after each of two shot peening intensities. The accuracy of the measurements of arc height was estimated to be ±0.01 mm. The progressive change in the height of the arc following exposure to elevated temperatures was obtained from the average of measurements of two specimens which were used for each combination of alloy, intensity of shot peening and time and elevated temperature of exposure, and using the following relationship

$$\alpha = \frac{h_t}{h_0} \times 100$$

where h_0 and h_t represent the arc height as measured prior to and after exposure to an elevated temperature, respectively. Table I gives the average values of the initial arc heights for the 2024 and 7075 aluminium alloys for two intensities of shot peening. For each alloy the arc height increases with the intensity of the shot peening. The greater arc heights for the 7075 compared with those for the 2024 aluminium alloy for the same intensity of shot peening are probably due to the 7075 aluminium specimens being thinner.

3. Results

3.1. Residual stresses

The effect of exposure to elevated temperatures on the level of residual stress in specimens of the 2024 and 7475 aluminium alloys prior shot peened to 5C (17.5A) Almen is shown in Figs 3a and b, respectively. Stress relief is observed for all the temperatures in the range 80 to 120° C, its rate and extent increasing with increasing temperature. The extent of stress relief also increases with time of exposure, albeit decreasingly so. For a temperature of 120° C, the level of residual stress is reduced by about 60% and 68% for the 7075 and 2024 aluminium alloys, respectively, after 40 h exposure. For temperatures of 110, 100 and 95° C and an exposure period of 200 h, the level of residual stress is reduced by 60%, 50% and 40%, respectively, for the 7475 aluminium alloy, and by about 55%, 50%

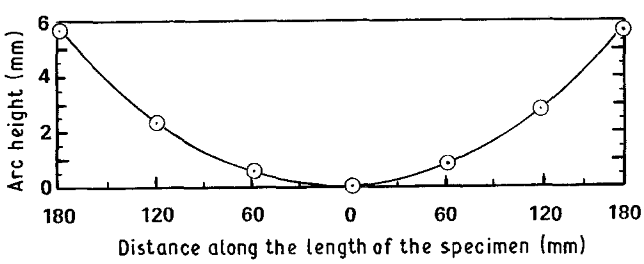

Figure 2 Typical symmetry of measurements of arc height.

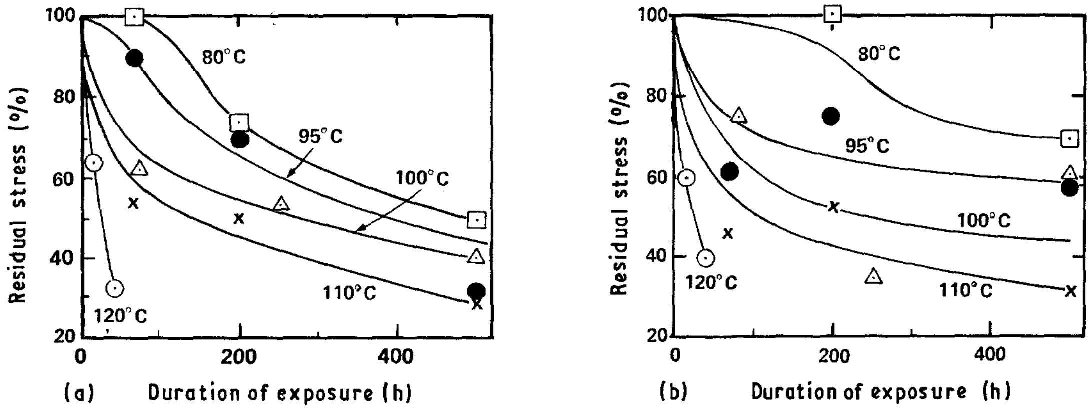

Figure 3 The effect of exposure at elevated temperatures on residual stress. (a) 2024-T851, (b) 7475-T7351. (□) 80° C, (●) 95° C, (△) 100° C, (x) 110° C, (○) 120° C.

and 30%, respectively, for the 2024 aluminium alloy. Further exposure at these three temperatures resulted in further but much less stress relief. For a temperature of 80° C the initial rate of stress relief was very slow for times up to 200 and 100 h for the 7475 and 2024 aluminium alloys, respectively. However, after 500 h exposure, the extent of stress relief was about 30% and 50%, respectively. The extent of reduction of residual stress was significant experimentally and practically for all the conditions of exposure, and fairly similar for the two alloys. Fig. 4 shows the effect of the prior intensity of shot peening on the subsequent relief of residual stress in specimens of the two alloys exposed for 250 h at 100° C. It will be seen that the extent of stress relief on such exposure increases with the intensity of prior shot peening.

3.2. Change of shape

Fig. 5 shows that, for both alloys studied, arc height decreases with increasing time of exposure at all the temperatures studied, i.e. the specimens tend to straighten out.

The initial change is rapid and increases with the temperature of exposure. Both alloys behave similarly. For both alloys, no significant difference in behaviour was found between specimens prior shot peened to 7A or 17.5A (5C) Almen. In every case the extent of change of shape measured as a percentage of original arc height is less than the percentage change in the level of residual stress.

3.2.1. The effect of abnormally high temperatures

Although in the major parts of the present work the highest temperature of exposure was 120° C which approximately represents the maximum temperature likely to be encountered as a result of aerodynamic heating in most supersonic flights of civilian or military aircraft, there are specific conditions where higher temperatures may be encountered. One such is in the curing at 160° C required in a sealing process termed Scotchweld [3]. Accordingly a 7075-T76 aluminium alloy specimen saturation shot peened to an intensity of 5C Almen was exposed for 3 h to a temperature of 160° C. At the end of the exposure the arc height of the specimen was reduced by 35%. This result is in keeping with those in Fig. 5, namely the higher the temperature of exposure the greater the straightening out of the specimen.

3.2.2. The effect of restraint during exposure at elevated temperatures

Because significant changes of shape were observed on exposure of shot peened specimens to elevated temperatures, it was of interest to determine what would happen when the specimens were clamped to rigid fixtures in simulation of assembly practices in aircraft. Accordingly 7075-T76 aluminium specimens of dimensions 130 mm × 330 mm × 4 mm were saturation shot peened on one side with 100% coverage to an intensity of 7A Almen using steel balls of size number 230 to 280. These specimens were clamped to a jig of dimensions 150 mm × 340 mm × 31.7 mm made from a 7075 aluminium alloy plate. The clamping was done by means of four threaded 1/4 in. (6.4 mm) diameter bolts whose centreline was 25 mm from the ends of the clamp. The ends of the jig face were tapered over a length of 25 mm and to an angle of 2.5° to restrict bending of the ends of the specimens which were clamped with their concave side to the jig. The change in arc height of one specimen was measured periodically during exposure for a total period of 19 h at 100° C without removing the specimen from the clamp. A second specimen was exposed clamped, but was released periodically to allow arc height to be measured. A third specimen was exposed but without clamping. The changes in arc height for all three specimens are shown in curves A, B and C respectively in Fig. 6.

The permanently free specimen showed the greatest change of shape. The specimen unclamped to facilitate measurements showed almost as much change of shape as that permanently free. The specimen permanently clamped showed only a small change in shape. Specimens which were shot peen formed on one side to a curvature similar to the foregoing, and then

TABLE I Initial arc heights

Alloy	Almen	Initial arc height (mm)	Standard deviation
2024	7A	3.2	0.6
2024	5C	4.3	1.0
7075	7A	4.1	0.6
7075	5C	6.0	0.5

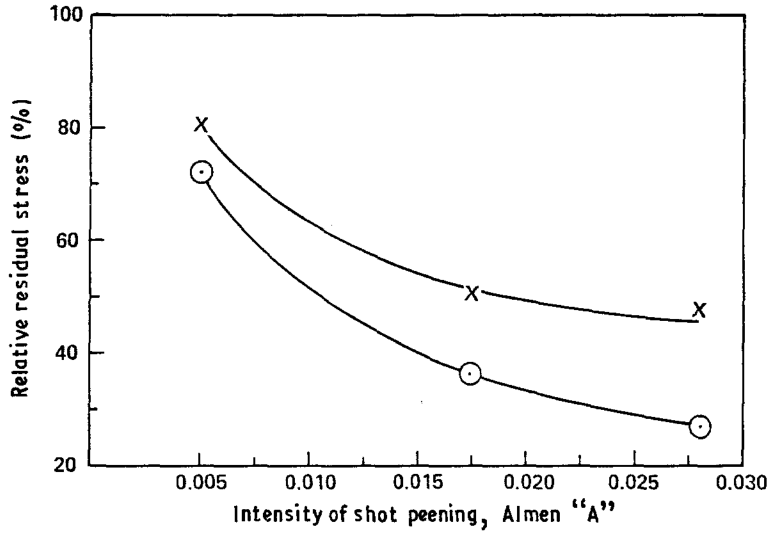

Figure 4 The effect of the intensity of shot peening on residual stress measured after 250 h, 100° C. (x) 2024-T851, (O) 7475-T7351.

saturation shot peened on both sides to an intensity lower than that used in the forming, were exposed as in the latter three specimens. The results are shown in Curves D, E and F in Fig. 6. The clamping and exposure conditions for D, E and F correspond to those for A, B and C, respectively. Shot peening on both sides of the specimens after shot peen forming resulted in smaller changes of shape than shot peening on one side only for all the conditions of clamping and exposure to elevated temperatures.

3.2.3. *Means for restricting change of shape on exposure at elevated temperatures*

Because the extent of change of shape increases with the temperature of exposure, it was considered that prior exposure at a given temperature should prevent or restrict further change of shape at a lower temperature. Accordingly a 7075-T76 aluminium specimen saturation shot peened on one side to an intensity of 7A Almen and one shot peen formed and then peened on both sides to a lower intensity as previously were exposed for 2 h at 120° C and subsequently for a further 19 h at 100° C. These specimens showed a reduction in arc height of 14.3 and 2%, respectively, after exposure at 120° C and a further reduction in arc height of only 1.2% and 0.4%, respectively, on subsequent exposure at 100° C, all in keeping with expectations. Without the preventive treatments, exposure at 100° C would have given reductions in arc height of 14% and 4%, respectively.

4. Discussion

Potter and Millard [4] carried out some tests on the thermal relaxation of residual stresses induced by shot peening in 7075-T6 aluminium specimens. The level of residual stress after shot peening was in the range 20×10^3 to 40×10^3 p.s.i. (138 to 276 MPa) in compression, comparable to that in the present work. Specimens exposed for up to 16 h at 200° F (93° C) showed no reduction of residual stress. However, after exposure at 225° F (107° C), reduction of residual stress commenced after less than 10 h exposure and the stress had decreased to 50% of the original value within 30 to 50 h. This compares with a reduction of about 35% for 50 h exposure at the same temperature from the present results for the 7475 aluminium alloy. Potter and Millard's specimen exposed for 16 h at 93° C was subsequently exposed for a further 30 h at 250° F (121° C). This resulted in approximately a 50% reduction in the original level of residual stress. This compares with a reduction of 53% for 30 h exposure at 120° C for the 7475 alloy in the present work. It is felt that had Potter and Millard [4] exposed their specimens for periods longer than 16 h at 93° C they would have observed reductions in residual stress. The agreement between the two sets of data is considered to be good.

Parts formed to a specific curvature by shot peening tend to straighten out on exposure to temperatures of 80° C or over. Should such parts be clamped rigidly, as in assembly in an aircraft, they can result in

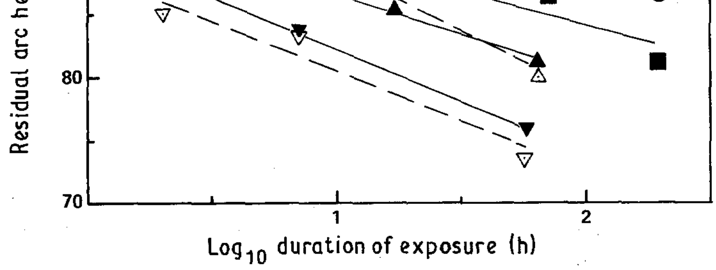

Figure 5 Effect of exposure at elevated temperatures on arc height. Solid symbols, 7075; open symbols, 2024. Temperature (° C): (●, ○) 80, (■, □) 100, (▲, △) 110, (▼, ▽) 120.

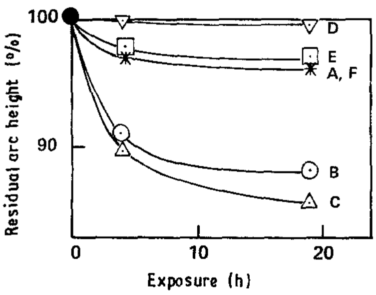

Figure 6 Effect of clamping on arc height during exposure at 100° C. (×, ○, △) Peened on one side only, (▽, □, +) formed, then peened on two sides. Specimen condition for measurement: (×, ▽) clamped; (○, □) freed; (△, +) permanently unclamped.

unanticipated bending or tensile forces on the mechanical fasteners used in assembly. Calculations have shown that for exposure for about 50 h at 120° C, a shot peened component made of 7075-T76 aluminium, 4 mm thick, and fastened by means of rivets of 4 mm diameter, the tensile stress acting on the rivets as a result of the component tending to straighten out could be of the order of 27 MPa. This is not an upper limit. Furthermore, because it is approaching a level at which consideration would have to be given to the size and type of fastener to be used, the implications are that the possible effect on fasteners cannot be neglected.

Aerodynamic surfaces frequently have complex curvatures which are amenable to production by shot peening. Clearly, consideration would have to be given to temperatures anticipated in service if these parts are to retain the efficacy of their design.

It will have been noticed that where relief of residual stress was significant, as measured in per cent, the corresponding percentage decrease in arc height was considerably less. This can be explained by the fact that the original arcing of the specimen due to shot peening is a combined effect of plastic and elastic deformation. Stress relief can affect only the elastic distortion. This will therefore always be relatively small as a percentage of the total deformation. The residual stresses are elastic and are amenable to total removal on thermal exposure. Accordingly relatively larger changes are to be expected in the relief of residual stress than in the straightening out of the specimens. Clearly the percentage decrease of only the elastic distortion would be expected to be comparable to that of the residual stress. Should the adjacent part be less rigid than that tending to straighten out, it too might tend to distort.

5. Conclusions

Parts made from 2024, 7075 and 7475 aluminium alloys and shot peened, whether for purposes of increasing fatigue strength or stress corrosion resistance, can lose some of these beneficial properties as a result of exposure to relatively moderate elevated temperatures. All the alloys behaved similarly in these respects. Induced residual compressive stresses can be reduced by as much as 60% after 40 h at 120° C and by 30% to 50% after 500 h at only 80° C.

Parts shot peen formed to a given radius tend to straighten out at temperatures of 80 to 120° C, the effect increasing with time and temperature. Such a change in shape, clearly undesirable in itself, can be accompanied by unanticipated bending and tensile forces on mechanical fasteners which could be of a significant level. Prior controlled exposure of a part shot peen formed can be employed to restrict subsequent change of shape in service.

The present maximum recommended temperatures of service for aluminium alloys warrant revision if parts are shot peened.

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