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Relaxation of Shot Peening Residual Stresses in the 7050-T7451 Aluminium Alloy after Heat Cycles for Adhesive Bonding

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1 Introduction

Shot peening, cold working of holes, and adhesive bonding of metallic or composite doublers are often used singly or in combination in order to increase the fatigue life of critical aerospace components. A doubler, applied to a highly loaded area, provides an alternate load path and can reduce the propensity for fatigue cracking. Adhesive bonding of a doubler requires a number of steps involving heat and pressure cycles where the temperature of the part might exceed the maximum temperature to which shot peened aluminium alloys should be subjected to, because of the possibility of thermal stress relaxation. The maximum exposure temperature ranges from 90 °C to 121 °C for aluminium alloys, depending on the shot peening specification used. [1] Slow relaxation of shot peening stresses in the 7075-T6 aluminium alloy heated to 225 °F (107 °C) has been reported. [2]

The following steps have been followed by the Canadian Forces to successfully adhesively bond a doubler to an aluminium alloy part, starting from a coating free surface, whether shot peened or not:

- grit blasting using aluminium oxide (220 grit) to produce a chemically active surface for the silane treatment and a rougher surface with greater surface area for the bond,
- application, and curing of a silane coupling agent (30 minutes at 175°F (79 °C)),
- application and curing of a corrosion inhibiting primer (i.e. Cytec BR127) (1 hour at 250°F (121 °C) preferred, or 30 minutes at 250°F (121 °C)),
- application of the adhesive (i.e. Cytec FM73M) and doubler, and curing of adhesive (2 hours at 250°F (121 °C) preferred, or 8 hours at 185°F (85 °C) at a pressure of 14.7 psi (101 kPa)). [3] The preferred cycles are preferred for bonding reasons only and not based on the effects on a shot peened article.

The Aerospace Materials Specification AMS-S-13165 states in section 3.3.10: "When peened parts are heated after shot peening ... the temperature employed shall be limited as follows: Aluminum alloy parts 200°F (90 °C) maximum". [4] This is qualified by section 6.13: "Processing or service temperatures of shot peened parts shall be limited to the temperatures in 3.3.10 unless test data for specific applications support the satisfactory use of higher temperatures". An experimental program was set up by the Canadian Forces to investigate:

- the effects of the low and high temperature cycles used for adhesive bonding on the relaxation of the shot peening residual stresses in the 7050-T7451 aluminium alloy,
- the effects of the grit blasting,

- the effects of a 2 hour exposure at 163 °C, as some areas of a part can reach that temperature in order to achieve the desired bondline temperature of 121 °C,
- and the effects of the low and high temperature cycles on fatigue crack initiation of shot peened 7050-T7451 aluminium alloy under a Canadian CF188 (F/A-18) spectrum loading.

2 Experimental Procedure

2.1 Specimen Preparation

Specimens, 12,5 or 25 mm thick, were machined from 7050-T7451 aluminium alloy plate. The design properties of the plate were: 440 MPa yield stress, 510 MPa ultimate tensile strength, and 10% elongation. [5] One surface was shot peened to an Almen intensity of 0,008 ± 0,001 A (inch) (0,200 ± 0,025 A (mm)) using Z425 ceramic beads per SAE J1830 and a minimum of 200% coverage, with saturation at 100% coverage. The grit blasting was performed using 220 grit aluminium oxide.

2.2 Residual Stress Measurements

The residual stresses were measured using a X-ray stress analyzer model AST X2001 over an area 3 mm in diameter using a chromium X-ray tube operating at 30kV. The Al 311 family of diffraction planes was used and the material X-ray elastic constant $E/(1 + \nu) = 57.1$ GPa was selected, where E is the modulus of elasticity and ν is Poisson's ratio. [6] To obtain a distribution of the residual stresses as a function of depth, material was electropolished away in increments of 0,025 mm. All the measurements were performed along two perpendicular directions coinciding with the plate longitudinal, transverse or short transverse orientations.

The measured residual stresses were not corrected for the relaxation occurring when layers of material are removed, because the correction would have been less than 5% for the peak stress, and the thickness of the compressive layer would not be significantly affected. [7] Direct comparison of the measured values was deemed satisfactory for this investigation.

2.3 Fatigue Specimens and Testing

The fatigue specimens, manufactured from 50 mm thick 7050-T7451 plate, were 254 mm long, 50.8 mm wide, 12,7 mm high and had a convex upper surface (Figure 1). The upper surface was shot peened as described in section 2.1. The specimens, designed for four point bending fatigue testing, provided a defined zone of inspection for crack formation, which was the primary concern of this study.

The specimens were fatigue tested in a computer controlled Instron 831 servo-hydraulic fatigue testing machine, using a spectrum gathered from flight data. One spectrum block consisted of 7719 cycles, representing 325 simulated flight hours (Figure 2). The loads were scaled up so that the specimens would fail within 80 blocks. Under these conditions, the peak stress, occurring once per block, was 513.3 MPa. The blocks were repeatedly applied. The specimens were inspected every 5 blocks for crack formation using acetate replicas and ultrasonic testing. Some tests were also run to final failure.

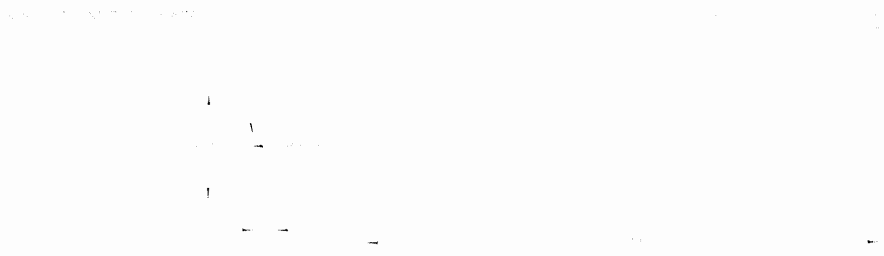

Figure 1: Fatigue specimen with a convex upper surface. The dimensions are in inches.

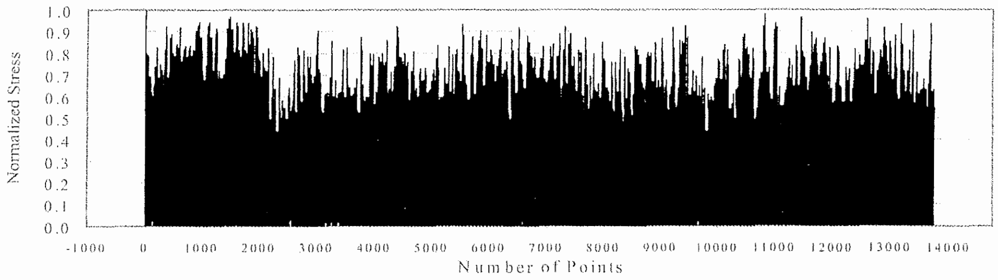

Figure 2: Normalized spectrum block representing 325 simulated flight hours. The maximum applied stress on the specimens was 513.3 MPa.

3 Results

3.1 Effects of 12 Hours Exposure at 85 °C

There was no relaxation of the surface and subsurface residual stresses after the following heating cycles of 30 minutes at 79°C, 4 hours at 85°C plus 8 hours at 85°C, initially considered for adhesive bonding.

3.2 Effects of Grit Blasting and a 2 Hour Exposure at 121 °C

The distribution of the residual stresses with depth was measured in two areas, one shot peened and one shot peened and grit blasted, in the as prepared conditions, and after one heating cycle at 121°C for 2 hours.

The compressive residual stresses increased from 248 MPa at the surface to a maximum of around 365 MPa, 0,025 to 0,050 mm below the surface. The layer with significant compressive stresses was 0,100 to 0,125 mm deep (Figure 3). The only effect of the grit blasting was a small increase of the compressive residual stresses at the surface, of the order of 10%. The heating cycle induced a relaxation of the compressive stresses. The effect was the most pronounced at the surface where the reduction was between 19 and 25% for the shot peened surface and between

21 and 29% for the peened and grit blasted surface. The relaxation of the compressive residual stresses was progressively smaller at greater depths (Figure 3). The peak compressive stress was reduced by about 10% from 365 to 330 MPa.

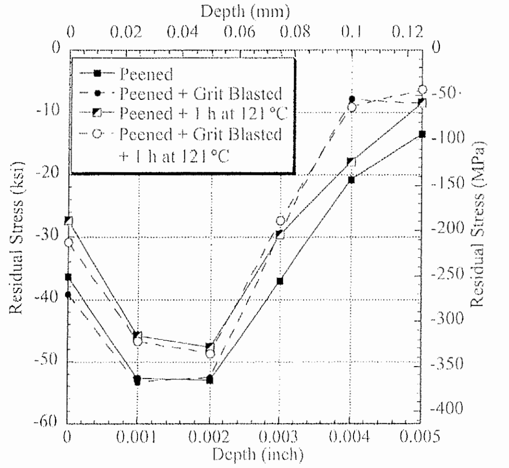

Figure 3: Residual stress distribution from a shot peened area and a shot peened and grit blasted area, in the as prepared conditions, and after one heating cycle at 121 °C for 2 hours

3.3 Effects of a 2 Hour Eposure at 163 °C

The distribution of the shot peening residual stresses with depth was measured in the as peened condition, and after one heating cycle at 163°C for 2 hours. The relaxation of the residual stresses was the most pronounced at the surface, where the reduction was between 30 and 40%. The residual stress relaxation was progressively smaller at greater depths (Figure 4). The peak compressive stress was reduced by about 20% from 330 MPa to 260 MPa.

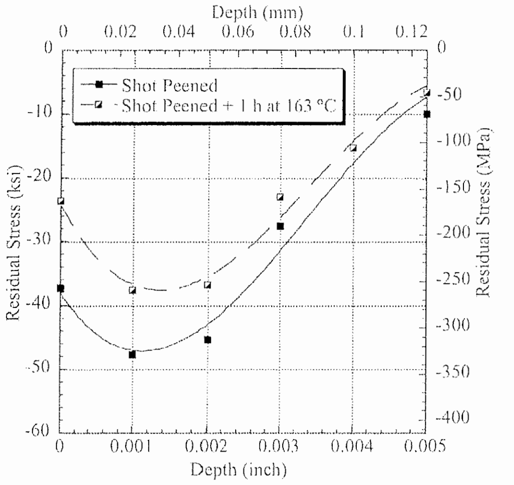

Figure 4: Residual stress distribution from a shot peened area, in the as prepared condition, and after one heating cycle at 163 °C for 2 hours

3.4 Effects of two Bonding Heat Cycles on Residual Stress Relaxation and Fatigue Life

3.4.1 Relaxation of Residual Stresses

The distribution of the shot peening residual stresses with depth was measured in fatigue specimens, in the as peened condition, and after heating cycles simulating all the adhesive bonding steps, one with a total time of one hour at 121 °C, and the other with a total time of 3 hours at 121 °C.

In the as peened specimen, the compressive stresses increased from 180 MPa at the surface to a maximum of 375 MPa, 0,100 mm below the surface. The layer with significant compressive stresses was approximaley 0,250 mm thick (Figure 5). That layer was deeper than those in the sections 3.1 and 3.2 specimens, also peened to the same nominal Almen intensity. The heating cycles induced a relaxation of the residual stresses, which was slightly larger after the longer exposure at 121 °C (Figure 5). The maximum relative relaxation was at the surface where the reduction was between 28 and 31 % after 1 hour at 121°C and between 31 to 39 % after 3 hours at 121°C. The peak compressive stress was reduced by about 16 % from 375 MPa to 315 MPa after 1 hour at 121 °C, and 23 % to 290 MPa after 3 hours at 121 °C.

3.4.2 Effects on Fatigue

Sixteen shot peened specimens were fatigue tested, 5 in the as peened condition, 5 after 1 hour at 121 °C, and 6 after 3 hours at 121 °C. Some tests were run to final failure. The results of the fatigue tests are summarized graphically in Figure 6. The average crack formation life (defined as the detection of a 1 mm long crack) for the baseline shot peened specimens was 69 blocks or 22425 simulated flight hours. Specimens exposed for 1 hour at 121 °C showed an average crack formation life of 43 blocks, a 38 % reduction compared to the baseline series. The average crack formation life of the specimens exposed for 3 hours at 121 °C was slightly lower at 40 blocks, a 42% reduction compared to the baseline series.

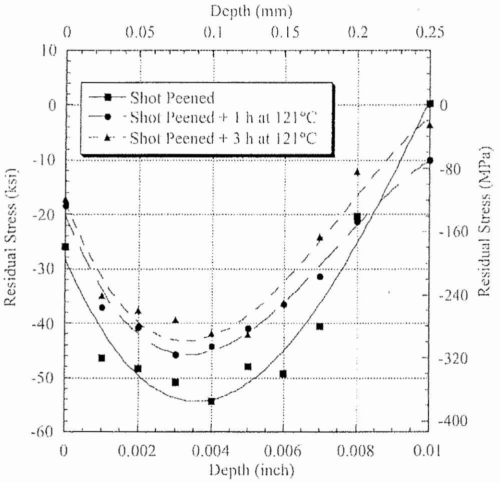

Figure 5: Residual stress distribution from a shot peened area, in the as prepared condition, and after 1 and 3 hours at 121 °C

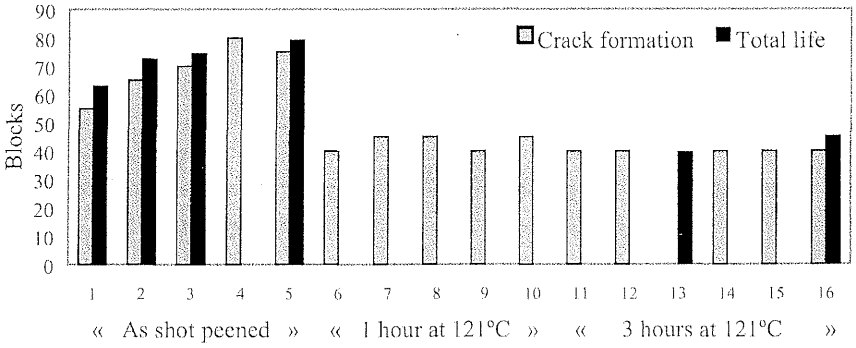

Figure 6: Crack formation and total lives of shot peened fatigue specimens tested as shot peened and after 1 and 3 hours at 121 °C

4 Discussion

Relaxation of residual stresses by thermal means is a function of temperature and time. There was no relaxation after an exposure of up to 12 hours at 85 °C. This is not unexpected as 85 °C was significantly below the lowest maximum permissible exposure temperature after shot peening. [1] After 1 hour at 121 °C, the maximum temperature to which shot peening parts should be subjected according to some specifications, the reduction of the surface stress was around 30 %. After 3 hours at 121 °C, the reduction of the surface stresses was between 31 to 39 %. A rapid decrease of the residual stresses with time followed by a more gradual one is typical of isothermal stress relief. [8] The relaxation of the shot peening residual stresses had increased to 30 to 40 % after 2 hours at 163 °C, but the maximum compressive stresses were still in the 255 to 275 MPa range. That temperature corresponds to the final aging treatment for the 7050-T7451 aluminium alloy. If the alloy is exposed to 163 °C for longer times or to higher temperatures, there will be a gradual decrease of the mechanical properties as well as a decrease of the shot peening residual stresses.

The only effect of the grit blasting was a small increase of the compressive residual stresses at the surface of the as shot peened specimen.

Adhesive bonding at the lowest possible temperature (i.e. 85 °C) would be the preferred choice if the prime objective was to minimize or avoid the relaxation of the shot peening residual stresses. A heat cycle of at least 1 hour at 121 °C to cure the primer is required to produce a durable bond, but this will lead to a relaxation of the shot peening residual stresses. The curing of the adhesive can be performed either for 2 hours at 121 °C or 8 hours at 85 °C. The 2 hour exposure at 121 °C could be selected based on ease of processing as the further relaxation of the stresses by this heat cycle would be small after the part has been exposed to the 1 hour at 121 °C primer cure.

The 1 hour exposure at 121 °C caused a significant reduction of the crack formation lives when the shot peened specimens were fatigue tested using a spectrum with a high peak stress of 513 MPa. It was reported that there was no significant changes in the fatigue life when specimens, shot peened to the same intensity and heated for 1,5 hours at 110 °C and 1 hour at 121 °C, were fatigue tested using a spectrum with a lower peak stress of 420 MPa. This is in accordance with the observation that shot peening is more beneficial to fatigue life at low stress levels. [9]

5 Conclusions

There was no noticeable relaxation of the shot peening residual stresses after an exposure of up to 12 hours at 85 °C.

The preferred heat cycle used for adhesive bonding, with a exposure of at least 1 hour at 121 °C, induced a relaxation of the shot peening residual stresses, which was maximum at the surface and of the order of 30%. There was a concomitant reduction of the fatigue crack formation life of the order of 40% when the specimens were fatigue tested under spectrum loading with a high peak stress. Subsequent sustained exposure at 121 °C had only small unappreciable effects on the residual stress relaxation and crack formation time.

6 References

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