THE EFFECT OF PEENING ON THE FATIGUE LIFE OF ALUMINIUM ALLOYS

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ABSTRACT

The RAAF F/A-18 aircraft makes use of a number of modern technologies; it has major composite structural components, cold worked holes and peened critical aluminium structural components. This paper reports on two test programs conducted at AMRL to examine the effect on fatigue life of the variables associated with peening 7050 aluminium alloy. In Part 1 of the program, the effect on fatigue life of a range of different peening processes is examined and in Part 2, the effect of a mid-life rework on fatigue life is investigated. The results indicate that at the test stress selected, peening provides a substantial improvement in the fatigue life of 7050 aluminium alloy. However, this improvement varies greatly and is related to the quality of the peening process as well as to the underlying material microstructure. While some success was achieved in relating surface roughness to fatigue life, the use of such an approach to quality control of the peening process proved unsuccessful, since fatigue life was controlled significantly by the larger sub-surface defects which could not be assessed directly. Part 2 shows that the original (peened) fatigue life can be restored by application of a suitable peening process during a rework; the process recommended is to polish the surface removing any original peening and then carefully peen with ceramic beads.

KEYWORDS

Aluminium, fatigue life, peening, rework, life extension

INTRODUCTION

Shot-peening is a surface cold working process used extensively in the aircraft industry to enhance the fatigue performance of critically-stressed high strength materials. Historically, peening with steel shot was applied widely to steels to improve fatigue life, and the technique is now used more widely on softer alloys such as aircraft aluminium alloys. In the RAAF F/A-18 there are a number of large fatigue-critical aluminium components that are peened in specific regions to provide an increased fatigue life.

Peening develops large surface compressive residual stresses by plastically deforming the material in the surface layer of a large elastic body. The expanded surface is elastically compressed by the substrate material, and this compressive residual stress is highly effective in enhancing fatigue performance, since it reduces the stresses acting on fatigue cracking which initiates and propagates from the surface. Unfortunately, peening also introduces surface damage, one obvious form of which is the production of laps/folds on the surface due to the local plastic deformation or impact extrusion of material parallel to the surface (Clayton and Clark, 1988). This surface damage is particularly significant in aluminium alloys, and is undesirable because, i) it reduces the life improvement factor otherwise obtained, and ii) it contributes to scatter in the fatigue life results. In some cases peening can actually reduce the component life due to the introduction of excessive surface damage (Simpson, 1984; Mutoh *et al.*, 1987; Clark and Clayton, 1990; Sharp *et al.*, 1994).

Two main questions are being addressed in the AMRL program, 1) how can the peening quality or characteristics be related to fatigue life, and 2) what factor of fatigue life improvement can be achieved by peening, and with what reliability?. This paper summarises some of the work being performed in this area at AMRL.

EXPERIMENTAL TECHNIQUE

Specimen Preparation

The material used for the study was 5 inch thick aluminium alloy plate conforming to the 7050-T7451 specification. Dogbone test specimens (approximately 230 mm x 65 mm x 6.5 mm) were machined from the plate. To remove any machining marks, and provide a consistent surface finish, all specimens were first dry abraded with #800 grade SiC paper on all surfaces. These large 7050 plates have a very heterogeneous microstructure, varying from almost the original cast structure in the centre of the plate to a highly worked structure on the surface of the plate (Barter *et al.*, 1990; Sharp *et al.*, 1996).

The RAAF fleet contains components which have been subjected to a wide range of peening processes both in the course of manufacture and as a result of restoration of surface treatment after local rework machining. The original aircraft finish varied considerably, with some regions of major surface damage (Sharp *et al.*, 1996). In the course of local rework of some areas of major components, AMRL recommended an improved peening method, based on total loss of peening media; this approach provides a much better surface finish because all broken beads are eliminated, rather than being re-used. A further improvement was expected by the use of ceramic beads which fracture less on impact with the surface, and which therefore produce less surface damage.

Part 1 of the program examines the effect of several possible rework processes on fatigue of plain coupons (ie. on original material, rather than part-way through life). The peening was based on the original equipment manufacturer's (OEM) specifications but performed by Australian contractors. Part 2 examines the effect of pre-treatment (in the form of prior fatigue cycling, as might be the case in service) on the fatigue life achievable after rework.

Part 1 Surface Conditions

Specimens simulated an area of material which was reworked locally using an improved ('contract') peening method involving total loss of peening media, shortly after entry into service, or a 'ceramic bead' peen which might be expected to provide even better results.

C1. Hand polish (#1200 alumina paper),
C2. OEM peen - peening performed at AMRL to simulate original aircraft peen surface condition,
C3. 'Standard' rework - OEM peen (C2) followed directly by 'contract' peening (i.e. a direct overpeen)
C4. 'Two Stage' rework - OEM peen (C2), then polish off all visible signs of OEM peening, finish to #1200 alumina grit, inspect, and apply 'contract' peening,
C5. Ceramic bead rework - OEM peen (C2), polish to remove all visible signs of OEM peening, finish to #1200 alumina grit, inspect, and apply 'contract' peening with ceramic beads.

In all cases, the 'contract' peening was completed by the RAAF contractors according to the OEM's specifications PS14023. The standard method involves establishing the time for 100% saturation, using a surface dye which is sprayed on and removed by the peening, and then peening to twice this (200% saturation) to ensure complete coverage.

Part 2 Surface Conditions

This part of the program involved demonstrating the capability of peening to restore the original specimen life when applied part-way through service, and was based on fatigue cracking specimens for a period representative of service, then removing both the original damaged layer and any fatigue cracks which had grown, followed by re-application of a 'contract' peened layer.

F1. C2 - fatigue for 3000SFH[1] - C4 -test to failure
F2. C2 - fatigue for 3000SFH - C4 -fatigue for 3000SFH - C4 - test to failure
F3. C2 - fatigue for 3000SFH - C5 -fatigue for 3000SFH - C5 - test to failure
F4. C2 - fatigue for 6000SFH - C4 - test to failure

To ensure that any cracks were removed before repeening, during the C4 or C5 reworks 200-300μm of material was removed from each face by hand-polishing. This depth was based on the maximum crack growth of about 100μm observed for cracks at 3000SFH in an unpeened structural test (Anderson and Revill, 1990), with an additional confidence cut to allow for the change in spectrum loading between the two tests. The amount of material removed was very conservative, since the crack growth rate through the peened layers would be very much slower than in the unpeened specimen. Before each stage of fatigue cycling the specimen dimensions were measured and the applied load corrected to achieve the peak nominal stress of 394 MPa.

Mechanical Tests

Specimens were tested under spectrum loading in a servohydraulic test machine operated at 5 Hz. The spectrum simulated military aircraft loading, with one program representing approximately 1 year's flying. The loads were scaled so that the peak specimen stress simulated the peak stress in the critical area of the component. The nominal specimen peak stress was 394 MPa.

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[1] Simulated Flying Hours

EXPERIMENTAL RESULTS AND DISCUSSION

Results Part 1

The first experimental series examined the effect of the rework processes on plain coupon with no prior fatigue. The results for all treatments are shown in Figure 1, with a summary in Table 1. Surface roughness data was obtained using a laser-based (i.e. non-contact) system.

Table 1. Summary of Part 1 fatigue lives.

Designation	**Sample Treatment**	**Log Average Fatigue Life (SFH)**	**Surface Roughness (µm)**
C1	Hand polish (no peen)	9287	2.9
C2	Simulated OEM peen	19079	46.5
C3	'Standard' rework (overpeen)	15073	38.0
C4	'Two Stage' rework (polish & re-peen)	22895	21.4
C5	Ceramic bead peen	30324	20.6

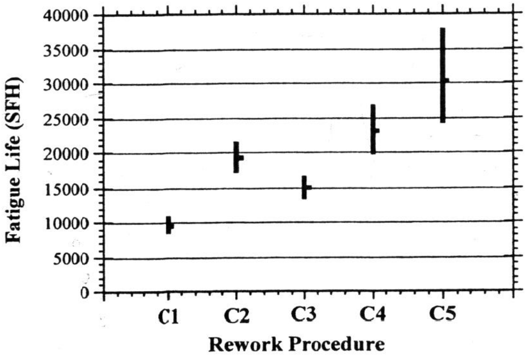

Fig. 1: The fatigue life results, showing the log average fatigue life (5 specimens were tested). The bars indicate ±1 standard deviation.

These results show that at this test stress, all peening provides an enhancement in fatigue life compared to a polished finish. The fatigue life ranking of the rework surfaces correlated reasonably well with surface roughness except for the C3 rework, Fig. 3, which was smoother than the C2 rework, Fig. 2, but had a shorter life. This shorter life was due to the increased number of deep laps/folds from any original surface defects being hammered deeper (i.e. being made more severe, while the surface roughness was reduced somewhat). This C3 process can be considered similar to 400% peening coverage (time to Almen saturation x 4), which has been reported to be detrimental to fatigue life by a number of researchers (Simpson, 1984; Mutoh *et al.*, 1987; Clayton and Clark, 1989).

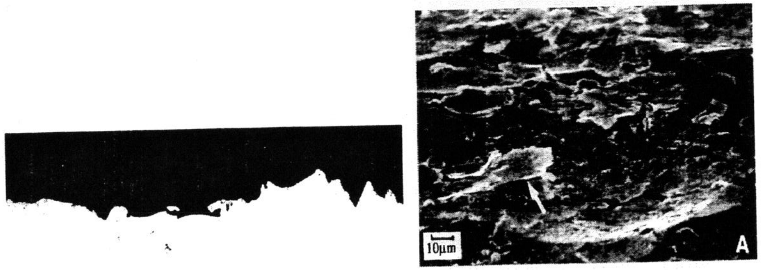

Fig. 2: AED simulation of aircraft service peening (C2).

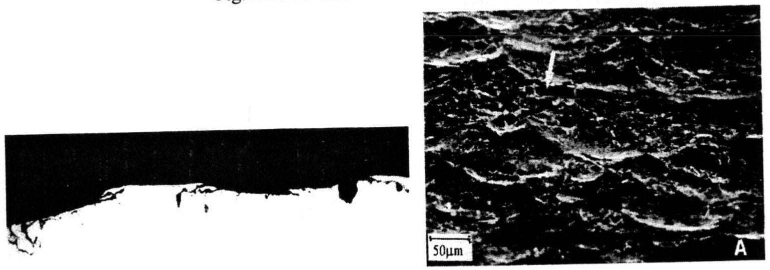

Fig. 3: The surface finish due to the standard stage rework (C3) without polishing the surface between the original peen and the rework peen.

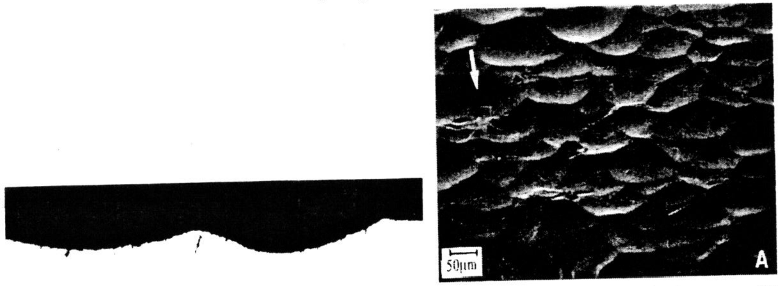

Fig. 4: The surface finish due to the two stage rework (C4) were the original peen is removed before the rework peen is applied and the rework peen is a total loss glass bead system.

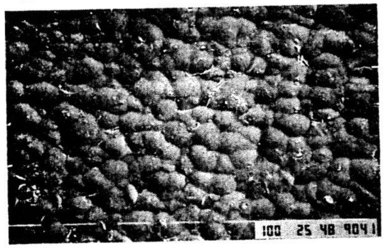

Fig. 5: SEM picture of the surface finish from a replica off the fleet aircraft, which is similar to fig. 4.

As the peening improved, the material properties appeared to be the controlling life factor. In both the C4, figure 4, and C5 reworks, the high and low fatigue lives appeared to be related to the location in the plate from which the specimen had been machined. The good (surface) microstructure provided the high lives and poor (core) microstructure the low lives. More coupon tests are in progress to confirm this result using a greater number of spcimens.

X-ray residual stress measurements showed a slight reduction in residual stress after testing, though an increased variation in the results. Where the x-ray residual stress was fairly consistent (approximately -250 ± 30 MPa) before testing for all rework processes, after testing the residual stress results varied from -209 to - 250 ± 20 MPa. This may indicate a change in the residual stress profile (residual stress relaxation) from fatigue cycling. A similar result has been reported by a number of researchers (Oshida and Daly, 1990; Hammond and Meguid, 1990). A major difficulty in this area is that of measuring accurately the residual stress profiles below the surface.

Crack growth rates were measured from fractographic observations on the fracture surface, and examination of the crack growth rate versus crack length curve, Figure 6, reveals the characteristic plateau region associated with crack growth through a surface residual compressive stress field. The position of the plateau region gives an indication of the approximate extent of the residual stress field (Clark, 1991) i.e. approximately 200μm for the peened specimens.

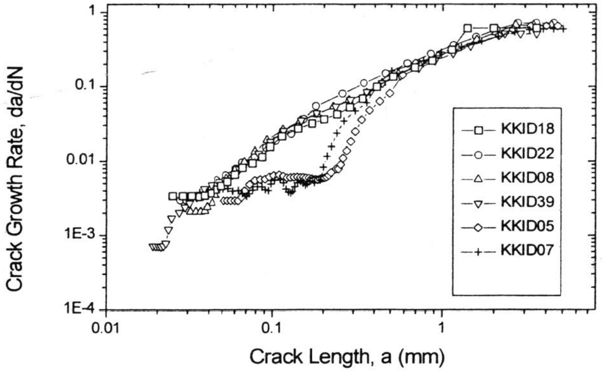

Fig. 6: Crack growth rate (N= program) versus crack length, comparing polished coupons with glass bead peened coupons. The plateau region on the peened plots is characteristic of crack growth through surface residual compressive stress fields.

The results, overall, from Part 1 show that peening is beneficial to fatigue life at the stress used in these tests. It would appear that peening directly over peening can be detrimental to fatigue life in comparison to other peening processes, and this process was regarded as unacceptable and rejected for Part 2. For Part 2, all rework processes involved polishing-off the original peening prior to repeening.

There appears to be an inverse relationship between surface roughness and fatigue life, however, the sub-surface damage folds and crevices resulting from poor peening, which cannot be measured directly and which are not reflected in surface roughness measurements, and a major factor which can distort this relationship. Thus the prospect of using surface roughness measurements as an indication of fatigue life seems remote at this stage.

Results Part 2

In part two the specimens were fatigued and reworked for various intervals to investigate the potential use of peening as a life extension process part-way through life.

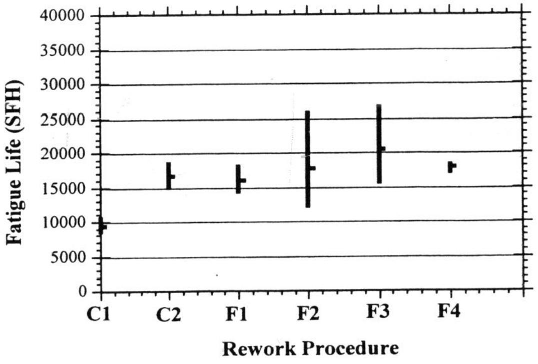

Fig. 8: The fatigue life results, showing the log average fatigue lives to failure after the final rework. The bars indicate ±1 standard deviation (since only 3-5 specimens were tested).

Table 2. Summary of Part 2 fatigue lives (averages based on three and five specimens).

Designation	Sample Treatment	Log Average Fatigue Life (SFH)	Total Fatigue Life (SFH)
C2	Simulated OEM Peen	16550	16550
F1	C2 - fatigue for 3000SFH - C4 -test to failure	16026	19026
F2	C2 - fatigue for 3000SFH - C4 -fatigue for 3000SFH - C4 - test to failure	17624	23624
F3	C2 - fatigue for 6000SFH - C4 - test to failure	20327	26327
F4	C2 - fatigue for 3000SFH - C5 -fatigue for 3000SFH - C5 - test to failure	17865	23865

Statistical analysis of the above results indicates that the only significant differences in life are between the original polish and all the peened results; there is also a significant reduction in scatter associated with the use of ceramic bead peening.

There are some interesting observations from the above results. Firstly, in each case the original fatigue life of the component was restored by a rework/repeen. Secondly, the ceramic bead peen rework (F4) showed very small scatter in the fatigue results, though the final life to failure was comparable with the glass bead rework (F2), which is different from the results obtained in Part 1. In Part 1, peening processes provided a fatigue life improvement factor of 1.5 - 3.2 over a polished surface. In Part 2 this fatigue life improvement factor was 1.6 - 2.1.
Even with "good" process peening there are still surface defects, Figure 9, although they are substantially reduced in number and size compared to those resulting from "poor" process peening.

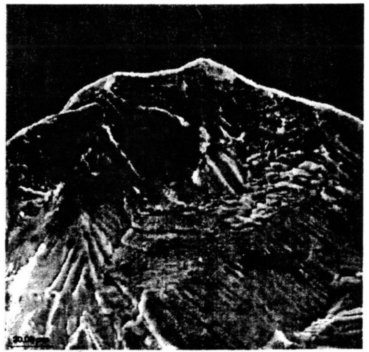
Figure 9: SEM picture of an fatigue initiating defect. Note folds and laps at corner.

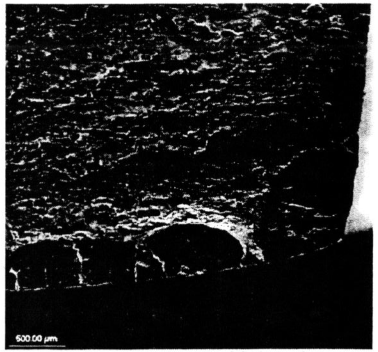
Figure 10: SEM picture of fatigue fracture surface. Note the multiple cracking.

The results show that peening can be continually applied, returning the component to its original fatigue life (allowing for reduction in thickness). It would also appear that greater improvements can be made in component fatigue life by completing the rework at the correct interval (compare F2 with F3), although care must be taken to remove enough material to ensure that any cracking present is removed.

CONCLUSIONS

1. At these stress levels (394 MPa) all peening improves the fatigue life of aluminium alloy specimens compared to a polished surface.

2. Over peening (i.e. extended-time peening) can lead to a reduction in fatigue life of aluminium alloys relative to the optimum condition. This should be examined in detail to fully determine the effects.

3. Ceramic bead peening significantly reduces the fatigue life scatter results. This is attributed to the reduced number of laps and folds on the surface ie surface defects.

4. The original fatigue life of a component can be restored more than once by careful rework and peening.

5. To achieve the maximum improvement in fatigue life, a rework process should remove the original peening by polishing (with a confidence cut for safety), followed by an inspection for cracks, and repeening with ceramic beads.

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