Pre-IVD etching removal and robotic shot peening retrofit on aircraft aluminium bulkheads

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Keywords: Robotic, Shot peening, Pre-Cycling, Fatigue Life, Aluminium, Pre-IVD Etching

Introduction

As a military aging aircraft depot level and in-service support contractor, L-3 MAS have been supporting fleets from many countries over the last 30 years in developing structural retrofit programs tailored to each of these aging aircraft to ensure both airworthiness and logistic risks are maintained to an acceptable level. As part of these retrofit programs, the use of in-situ Shot Peening is one of the structural life enhancement techniques that L-3 has mastered for over 15 years using robotic systems. The advantage of using a robotic system for shot peening is to improve quality, repeatability and allow to reach areas on aircraft where a technician would have no or very limited access. Up to recently, these shot peening retrofits were carried out prior to 70% of the expended fatigue life at each hot spot and assuming a Life Improvement Factor (LIF) of only 1.5.

A recent mandate was to provide structural enhancement via shot peening to 9 different Fracture Critical aluminum bulkhead hot spots on a fighter aircraft. Each location had a specific geometry, stress level, grain orientation, blue print (B/P) fatigue life, etc. Based on the most critical areas, a LIF of up to 3.0 was required with a retrofit induction as late as 80% of the location blue print life. Although L-3 did some coupon testing in the past suggesting such LIF should be attainable, the available test data were insufficient to certify that such LIF would always apply with enough confidence for all the specific physical characteristics of the new hot spots.

Thus, a new coupon test program was developed specifically to address these bulkhead locations. Moreover, due to the late induction time of these retrofits, a thin layer of material also needed to be removed prior to the shot peening to remove some of the accumulated fatigue damage.

Objectives

Demonstrate via a coupon test program that the targeted hot spots (9 on various bulkhead areas) will all be able to reach the targeted service life after a shot-peening rework. This test program must ensure all physical characteristics of the 9 hot spots are well represented, that the influence of the most important parameters are measured and that sensitivity of secondary parameters are evaluated. The blend depth required to remove sufficient accumulated fatigue damage prior to shot peening must be determined (the traditional default value of 0.003-0.006” will be used to start). Finally, the effect of shot peening on an undetected small crack (of known size) must be evaluated.

Methodology

A list of physical characteristics that could potentially affect the shot peening benefit at each location was generated. From this list of test parameters, a combination of parameters, providing either the most conservative or the most typical results for all of the critical locations, was selected based on experience and engineering judgment. This combination of parameters is used as the default test values for certification. The list is provided in Table 1 below.

The values on the right most column were used for what we called the Main Certification Test (test Group no 3 from the text matrix shown in Table 2 on p. 4). For the purpose of ensuring confidence on the repeatability of the results and to hopefully have a reliable measure of the scatter, the number of coupons per series for this test group was set to 30.

Table 1 List of Test Parameters

Characteristics	Test Values Considered	Default Value for Certification (Test Group 3)
Material	Aluminum 7050-T7451, plate, 6 inch thick	
Stress level (ksi)	53.5, 55.2, 62.9, 64.6, 72.5	64.6
Flaw Type	Surface in middle of radius and edge corner cracks	surface crack in radius
Fillet Radius (inch)	0.16, 0.25 and 0.38	0.16
Stress State	Pure uniaxial to some level of bending/shear	Uniaxial
Grain Direction	LT, TL and ST	LT
Marker Bands	Added or not added in spectrum	Added
Spectrum	Fleet 50th% to 90th% severity	90th%
Spectrum Truncation (rise-fall)	None or 30%	30%
Aluminum Manufacturing process	Early 1990`s and today	Today`s process
Retrofit Incorporation Time	30% to 80% of the unfactored fatigue life	80%
Pre Peening Blend Depth	0.003"-0.006" deep to 0.013"-0.016" deep	0.003" to 0.006"

From the list of parameters, some values were considered for "Conditional Tests" in case the Main Certification Test would provide results below target (i.e. the main test would certify only a limited number of hot spots). An example is the late incorporation time (pre-cycling at 80% of B/P life). This late incorporation could show too much scatter (due to defect size already present on some coupons) so some test series with a shorter pre-cycling (ex. 50% of B/P life) would allow to certify hot spots with such an earlier incorporation time. Then, to provide certification to the late incorporation time hot spots, a series of coupons with a deeper pre-peen blend would be tested until sufficient fatigue damage is removed.

Finally, even if the Main Certification Test demonstrates the required LIF of 3.0 in all cases, it is still required to know how sensitive some parameters would be on the effectiveness of shot peening, mainly if the LIF demonstrated is close to the target value (i.e. small positive margin).

Thus, "Sensitivity Tests" were defined with smaller number of coupons per series (qty 7). An example is the effect of the material grain direction (ST). Not all locations have the loading aligned with the LT direction. Thus, a test using the ST direction was conducted (ref. Group 5) to try to see how the grain direction would influence the Shot Peening LIF. If ST direction would provide unacceptable results, then coupons in the TL direction would be tested. Other sensitivity tests conducted were targeting the stress level (Ref. Group 2 and 2a), the flaw location/type (corner crack (Ref. Group 16) or surface crack), spectrum severity (Ref. Group 10) and coupon geometry (Ref. Group 1).

Coupon Geometry tested

The coupon geometry used by default for certification of the bulkhead pocket radii is show on Figure 1 below.

In order to verify the effect of the coupon geometry on the shot peening life improvement factor, we tested a series of coupon with a simple pocket shape (Figure 2a) at the same Kt and stress level as a previous test program that was using a more complex 3D shape (Figure 2b).

Finally, to test the shot peening on edge cracks, the geometry shown in Figure 3 was used.

Note that on all coupon geometries, the peened series were peened over the entire pockets (inside and outside) and including the radii near the grip ends.

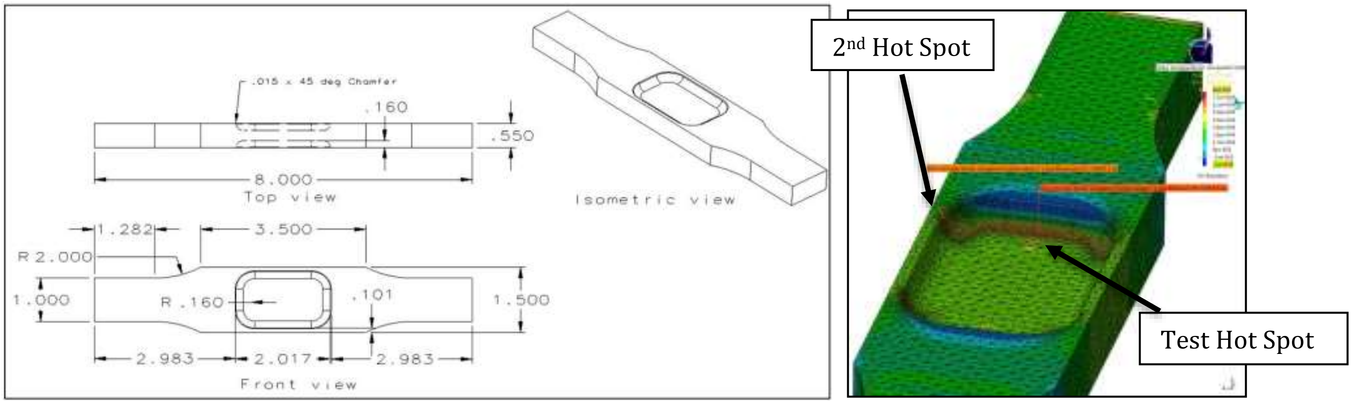

Figure 1: Coupon Geometry no 1

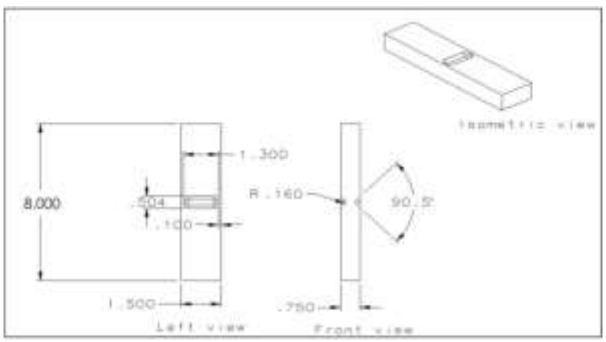

Figure 2a Coupon Geometry no 3

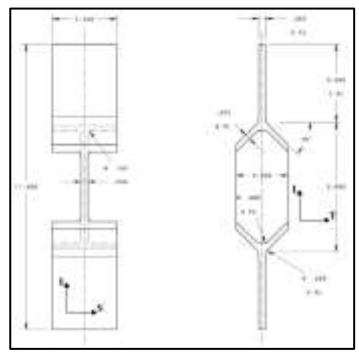

Figure 2b Previous Prog. Geometry

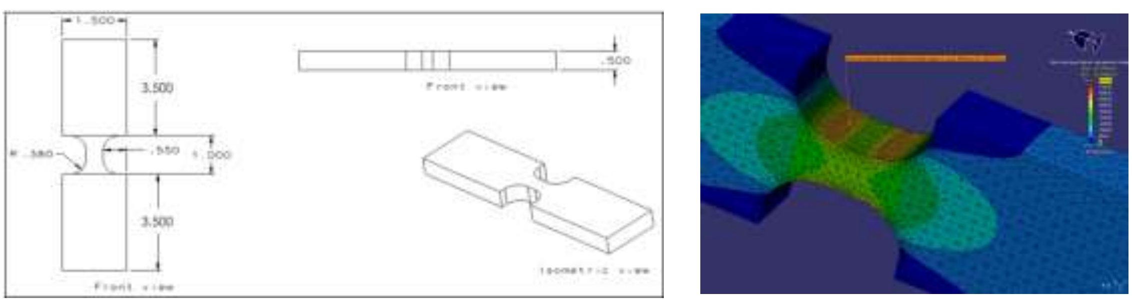

Figure 3: Coupon Geometry no 5

Test Matrix

From the test parameters/requirements discussed on the previous pages, a complete test matrix was built with a logical sequence so that most important test results are obtained first which can be used to either trigger or cancel the requirement for subsequent test series. This matrix covered a maximum quantity of 579 test coupons (if all conditional and sensitivity tests would be triggered). Fortunately, with the positive results obtained from the Main Certification Test, the program ended up requiring only 166 coupons. The test matrix is shown below (limited to the tested groups only).

Table 2: Test Matrix – Tested Groups Only

Sequential Number (Order)	Test Group ID	Test Group	Series Description	Ref. Location	Peak Stress (ksi)	Pre-cycling (% unfactored CI life)	Surface Blend	Number of Coupons	Coupon Geometry	Spectrum
1	1	Coupon 3D vs. 2D geometry	baseline	6	72.5	n/a	n/a	**7**	3	Historical
			early peen	6	72.5	0%	n/a	**7**	3	Historical
2	2	Stress level	baseline	6	62.9	n/a	n/a	**7**	3	Historical
			early peen	6	62.9	0%	n/a	**7**	3	Historical
3	2a	Stress level	baseline	6	55.2	n/a	n/a	**7**	3	Historical
			early peen	6	55.2	0%	n/a	**7**	3	Historical
4	3	Fillet late peen .003-.006"	Baseline	5	64.6	n/a	n/a	**30**	1	New
			Late peen nominal blend	5	64.6	80%	.003-.006	**30**	1	New
11	12	Damage Removal	Peen once crack of 0.015" is measured	5	64.6	at 0.015" crack	.003-.006	**15**	1	New
13	16	Edge Crack	Baseline	7	53.5	n/a	n/a	**7**	5	New
			early peen	7	53.5	0%	.003-.006	**7**	5	New
15	5	Grain direction ST	baseline	9	64.6	n/a	N/A	**7**	6	New
			early peen	9	64.6	0%	.003-.006	**7**	6	New
26	10	Spectrum severity (50th%)	baseline	5	64.6	n/a	N/A	**7**	1	New
			early peen	5	64.6	0%	.003-.006	**7**	1	New
28	11	Master Event Spectrum (IARP03a)	Baseline	2,5	64.6	n/a	n/a	**7**	1	Historical

Test Conditions

- Test and calibration performed at the National Research Council (NRC) of Canada in Ottawa
- Several servo-hydraulic machines from 22 to 55 kips
- Testing frequency: avg. of 8.25 hz
- Shot peening using robotic equipment: intensity of 0.008A +/- 0.001A with Z425 ceramics bead as per SAE J1830. Stand-off distance of 1 inch +/-0.25" with an angle of 90 deg +/- 25 deg
- Max load from 9,000 to 25,000 lbs depending on coupon geometry
- Spectrum loading (variable amplitude) with R ratio of approx. 0.3
- 2 spectra used: Historical: 23400 cycles/1000 hrs & Target spectrum: 11980 cycles/1000 hrs
- Failure criterion is a crack indication size of 0.010" (defined as Crack Initiation (CI))
- Inspection starts at approx. 80% of expected CI life using both surface eddy current and Enhanced LPI (ELPI), for every 5% of life until CI is detected.
- Quantitative Fractographic analysis is performed on several coupons of the same geometry and spectrum to calibrate NDI techniques for subsequent coupons
- All coupons except Groups 1, 2 and 2a were etched to simulate the pre-IVD etching applied during the production of the bulkheads (tends to accelerate fatigue crack onset)

Results and analysis

This section provides a brief summary of the coupon test results in terms of Life Improvement Factor obtained. The LIF is simply the ratio of the CI life from the Peened test series over the Baseline test series. We often quote both the average and factored LIF. However, the official LIF considered for certification is the factored LIF obtained from the ratio of factored lives which are defined as the log10 average minus 3σ.

Coupon Geometry & Stress Influence

Coupon test Group no 1 allowed to show that the relatively simple coupon shape used in this program (shown in figure 1) provides comparable results to the much more complex 3D shape used in the past (called "RCAF X19") suggesting the use of a complex coupon geometry is not mandatory. The factored LIF demonstrated for Group 1 was 3.9 vs 4.7 for the previous test program.

Test group 2 showed a LIF of 4.0 (average) and 8.2 (factored) while Group 2a showed a LIF of 4.7 (average) and 12.2 (factored). This shows that the life improvement provided by shot-peening was not sensitive to the stress level in the range studied.

Main Certification Test

The test Group no 3 baseline series (unpeened) average life was 7631 FH (Flight Hours) for a standard deviation (log10) of 0.082 and a factored life of 4246 FH. The peened series was pre-cycled up to 83% of the baseline series **life** (to be equivalent to 80% of the fleet baseline fatigue damage assuming a fleet life standard deviation of 0.1 instead of 0.082), blended .003”-.006” deep then peened. The problem seen with the improved coupons was that the shot peening rework performed so well at the hot spot radius that some coupons started to crack at other locations on the coupon: grip area & side of pocket (secondary hot spot).

Only 5 coupons cracked in the radius hot spot (green bars in Figure 4). 10 coupons failed at the secondary hot spot shown in Fig. 1, at the edge of the specimen (grey bars in Figure 4). 15 coupons cracked in the grips (black bars). These last 25 coupons did not reach CI at the radius hot spot. The problem of cracking at undesired locations was significantly reduced for subsequent tests with the use of scrim cloth in the grips and adding a smooth corner radius at the coupon edges prior to peening. Two of the five coupons that failed in the main radius hot spot had a clear crack signal after completion of pre-cycling (before being blended and shot-peened) and then were cycled up to a 5 and 6 times the non-peened specimen fatigue life before a 0.010” crack size appeared. The 3 other specimens that failed at the radii had much higher lives (between 10 and 14.8 times the non-peened specimen fatigue life). Conservatively, mixing all data (i.e. the 5 specimens with failure at the radius and the 25 specimens that failed at other locations without showing any crack indications at the radius), a log average life ratio of 8.4 is obtained. With the standard deviation of 0.154 obtained (twice as large as the baselines series and deemed exaggerated considering the mix of conditions), a factored LIF as high as 5.0 is obtained.

Various Sensitivity Test Results

Test Group 5 (ST grain direction) and group 10 (50^{th} percentile spectrum severity) showed that grain orientation and spectrum severity did not have any detrimental impact on the life improvement provided by shot-peening. Indeed, a LIF of 26 (on the average) and 9.0 (on the factored life) was measured for group 5 and group 16 showed a LIF of 10 (average) and 8.9(factored). Group 16, with the coupon geometry shown in figure 3 has shown that the geometry of the reworked area did not have effect on shot peening LIF to the point of not meeting the required LIF of 3.0.

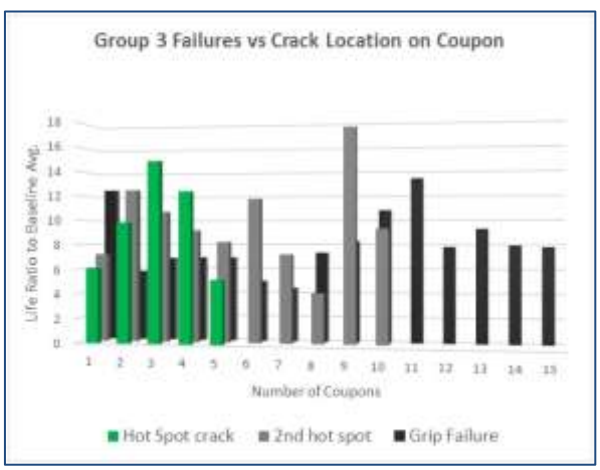

Figure 4: Group 3 Failure Data

Peening on a Known Existing Crack

15 coupons were pre-cycled to a crack depth of 0.015" then, the blend with shot peening modification was applied. Since a crack of approximately 0.010" already existed at the time of shot peening (crack of 0.015" blended only by .003" to .006"), an important scatter was expected. The purpose of this group is to see the level of scatter expected in case cracks are left undetected and to determine if the crack growth rate is affected by a tensile residual stress field. Crack growth curves obtained by quantitative fractography are shown in Figure 5, where yellow curves are for the non-peened specimens and the blue curves for the peened ones. As expected, a large scatter is observed for the CG life of the peened specimens depending on the initial crack depth when peening was completed.

Also, one can see an increase in the CG rate when the crack reaches a depth of 0.010" to 0.012" since the crack exits the compressive layer. After this depth, the CG rate is steady and fairly uniform among coupons. The CG rate becomes pretty much the same between a peened and non-peened coupon. Therefore, peened coupon CG rates are not accelerated by the tensile residual stress field beyond the compressive layer.

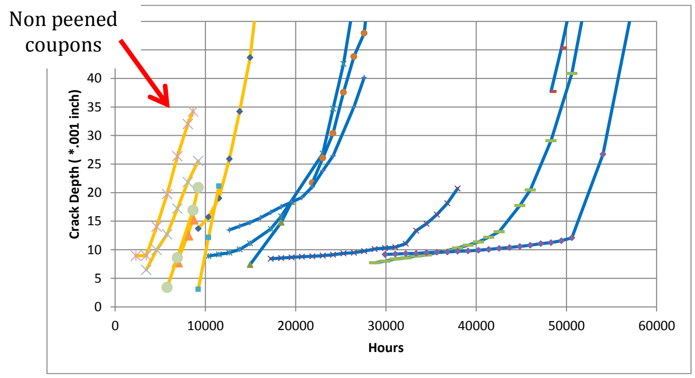

Figure 5: Crack Growth Curves

Conclusions

This study presents the results of a large experimental test campaign to assess the life improvement that can be provided by a polishing and shot-peening rework. The interest of the study is that it shows that high life improvement factors can be obtained under several different conditions (i.e. test parameters such as grain direction, geometry, stress level and fatigue spectrum shape). Even though several occurrences of secondary cracking at undesired locations were seen after peening, the main test series has shown a LIF as large as 5 when implementing the rework as late as 80% of the blue print hot spot average life. The LIF calculation procedure used herein accounts for the increase in scatter after peening.