Influence of Laser Peening (LP) and Shot Peening (SP) on Fretting Fatigue Life under Spherical Contact

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Abstract

This paper analyses the fretting fatigue behaviour of Al 7075-T651 processed with LP and SP. A special test specimen with “dog bone” shape was used to run all the tests. The experimental specimens were laser peened and shot peened under different parameters to compare their effect and efficiency with untreated specimens. The fretting fatigue was carried out in a spherical-plane contact Condition using a uniaxial servo-hydraulic machine. Residual stress distributions of some of the treatments were presented to evaluate the magnitude and depth of the residual stress distribution.

Keywords: Fretting, fatigue, shot peening, laser peening, aluminium

Introduction

The fretting fatigue is a phenomenon that appears between surfaces that are in contact and are subjected to cyclic loads. Cyclic forces, which combines normal, tangential and axial loading, are developed in the contact zones. In addition, a very small amplitude displacement happens between the two surfaces. Under these conditions, the nucleation of cracks and the growth of these nucleated cracks induce the final fracture of the component. This kind of phenomenon is very common in riveted and bolted joints, shrink-fitted couplings, metal ropes and cables, coil wedges in generation rotors and the blade-dovetail contacts sections in the gas turbine engines.

Due to the importance of the state of stresses in the bodies in contact, the introduction of a residual compressive stress in these zones are frequently used to avoid or mitigate the effects of fretting fatigue in real components like the above mentioned. Two fretting fatigue improvement methods, shot peening and laser peening are evaluated in this study on typical aluminium used in the aircraft industry.

Test description

Figure 1 shows a schematic of the loads applied in fretting fatigue tests. In the figure, three forces are presented, P, Q and σ. The normal load P is constant and the axial load σ is fully reversal ($R=-1$). The tangential load, Q, is induced through the contact pads according σ. In all tests, the ratio $Q/\mu P$ was lower than one ($Q/\mu P<1$) in order to produce partial slip between the contact surfaces [1]. The contact between the pads and the test specimens is spherical-plane. The tests were made with load control over σ at a frequency of 5 and 10Hz.

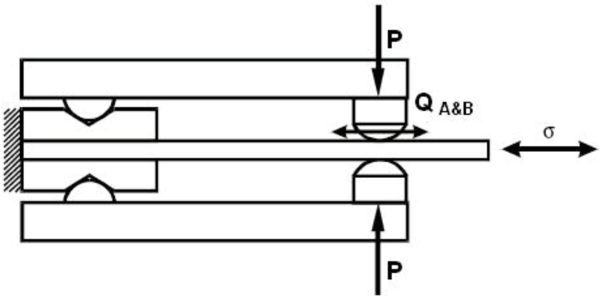


Figure 1: illustration of a fretting fatigue test machine

The shape of the test specimens is “dog bone” as showed in the figure 2. The specimens are fixed to the test machine by both threaded ends. The section of the specimens are rectangular to create a plane for the spherical-plane contact and the radii of the contact pads is R=0.1m. To adapt the sample to the loading capabilities of the servo-hydraulic testing machine, the section was reduce from 10x10 to 9x9 mm and loading was related to this change.

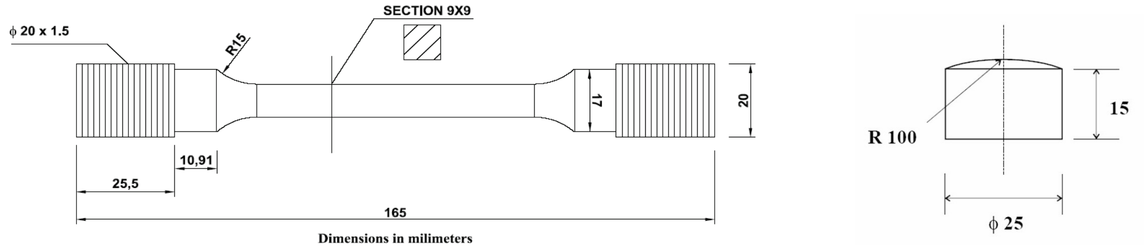


Figure 2: Dimensions of the dog bone specimens with contact pad

Table 1: Mechanical properties of Al-7075-T651

Yield limit	σ_y	503 MPa
Young’s module	E	71 GPa
Poisson’s ratio	ν	0.33
Fatigue strength coefficient	σ_f'	1610 MPa
Fatigue strength exponent	b'	-0.1553
Cyclic strength coefficient	K'	694 MPa
Cyclic strain hardening coefficient	n'	0.04
Crack growth coefficient (R=0)	C	$4.83 \cdot 10^{-11}$
Crack growth exponent (R=0)	m	3.517

The material in this study is Al-7075-T651 with the mechanical and fatigue properties shown in table 1. These properties have been obtained from the references [1] and [2]. The fatigue life without fretting is calculated as 41.10^6 cycles with an axial load of 95 MPa (R=-1). When the axial load increases to 125 MPa, the fatigue life reduces to 7.10^6 cycles. With fretting-fatigue condition presented in this paper, the fatigue lives under two axial loadings drop to 270 845 and 65 614 cycles, respectively.

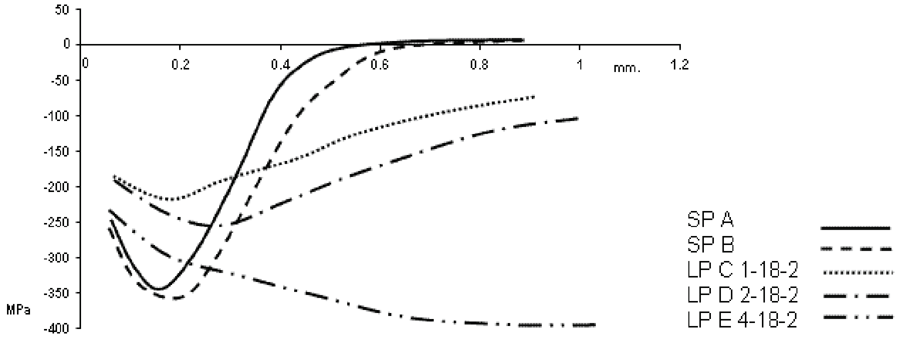
Two SP conditions, SP A (BA 600N – F20-24 A – 100%) and SP B (BA 800N – F25-35 A – 100% + BV300 F10-15A – 100%) were considered. SP parameters type A are very usual parameters in the aircraft industry. BA 600 N is equivalent to S230R. Cast steel shot diameter 600µm hardness 45-52 HRc. Almen intensity: F20-24A is equivalent to 8-10 A. 100% means full coverage. SP type B is an experimental process to study the effect on fretting fatigue by increasing the depth of compressive stress with a bigger shot diameter with higher intensity. It was also decided to reduce roughness with a second SP process with glass bead. BA800N is equivalent to S330R. F25-35A is equivalent to 10-14 A. BV300 F10-15A is glass bead Peening using 4-6A.

Four LP parameters were selected. LP C (1-18-2); LP D (2-18-2); LP E (4-18-2) and combined peening case F (LP E + SP A). For the description of the LP, the first figure represents the power density in GW/cm², the second figure represents the pulse width on the surface of the material in ns (nanoseconds: 10^{-9} s) and the last figure is the number of passes on the material.

MIC has used the LP process in production for six years and 3 facilities are operating in 3 shifts. This technology is really successful to induce compressive residual stress on metallic components

and especially on aircraft engine parts. Nevertheless, it was the first time to ask MIC to evaluate LP against fretting fatigue life on aluminium. Since SP is frequently required on aluminium aircraft structural components to improve fretting fatigue life, it is interesting to compare the LP with the SP under the same test conditions.
An additional glass bead Peening was processed on the thread on most of the dog bone samples after discovering failures in this area instead of the contact point.

Residual stress analysis
The residual stress distribution for SP and LP were analysed. The hole drilling method, in conjunction with the integral, is used to measure the residual stress profile. The measurements were carried out with the ultra-high speed system MTS3000 from HBM. The type of strain-gage rosette used to measure the strains was the Vishay 062RE-120-EA, which allows obtaining the residual stress field accurately up to an approximate depth of 1mm. Due to the difficulty of the measurement of the residual stress on a sample with roughness, the first point near the surface was rejected and the value at the depth of 0,069mm was taken as the first value. Then, the residual stresses from 0.069 to 1mm were analysed.
A dedicated specimen with the same material of the “dog bone” was manufactured to process LP and SP and analyse residual stresses.



Figures 4 shows the residual stresses profiles after different treatments mentioned above.

Residual stresses distribution achieved from SP are typical on this material. Maximum residual stress is -350 MPa and we increase the depth with more Almen intensity. The value of intensity is limited by the potential detrimental roughness.

Three (3) power densities were used for LP. Residual stress distribution was improved with 2 and 4 GW/cm² without detrimental effect like distortion or roughness.
The MIC Laser technology is based on a Neodymium glass technology and is able to achieve 15 GW/cm². Then, 6 or 7mm of compressive residual stress can be achieved if necessary on aluminium. This can be very interesting to enhance damage tolerance.
The low cold working from LP with 2 layer combined with low energy make a maximum compressive stress 100MPa lower than SP.
This cold working effect can be a major issue during the development of an application according the material and the working conditions. LP allows an accurate control and high level of repeatability of cold working effect.
For this reason, titanium can be a very good candidate for LP.

Surface roughness and friction coefficient

Roughness is, of course, an important parameter for fretting. The service stress developed in the contact zones are influenced by surface finishing [5] with the consequence in variation of fatigue life. For this reason, the roughness was analysed, these parameters are shown in table 2 for the different conditions of surface finishing.

Table 2: Parameters of surface roughness

Process	Ra(µm)	Rz(µm)	Rt(µm)
As machined	0.53	2.90	2.90
SP A	6.37	39.87	57.00
SP B	5.77	35.40	48.93
LP C	1.07	8.47	10.13
LP D	1.40	11.07	13.47
LP E	0.5	2.00	3.33
LP+SP F	3.36	23.53	41.67

It is well know that increasing roughness on a material reduces the fatigue life of the same material but when SP or LP are processed, the situation is completely different because we introduce a very high magnitude of compressive residual stress.

In this fretting fatigue study, we have also to consider the contact metal-metal which create the damage where crack initiation is located. This is the reason why it is interesting to put in relation roughness and friction coefficient.

Note, the roughness value concerning LP E. We would have expected something about 2µ for Ra instead of 0.5µ for Ra. The reason is probably because the geometry is shows waviness with 3mm large. Then location of measure is sensitive.

The friction coefficient is a fundamental parameter in the fretting fatigue problem, because the stresses developed in the contact zone are dependent on the value of this coefficient, and therefore the life of components subject to fretting fatigue. The coefficient of friction has been measured with the same machine that was used for the fretting fatigue tests. The procedure to obtain this coefficient is developed extensively by some authors [4]. Table 3 shows the values of the coefficient of friction for the configuration pad/specimen obtained for all the different treatments. In this study, the pad is always in condition "as machined" and the following processes are used on the dog bone specimen. It is already planed to evaluate the friction coefficient with shot peening on the pad on next study.

Table 3: Coefficients of friction

Process	SP A	SP B	LP C	LP D	LP E	L+SP F	As machined
µ	1.03	1.02	1.32	1.19	1.18	1.12	1.2

Results of the experiments

Fretting-fatigue is a complex progressive damaging process where there are lot of inter connexion between the different variables like axial, normal and tangential loading but also all the tribology aspect are important in the results like surface finishing, value and geometry of the roughness on each surface in contact.

On other hand, some unexpected failures occurred outside of the contact point. Some of them were initiated in the thread and some others in the edge of the square section. An additional specific glass bead peening was processed on the thread of dog bone samples and it results an efficient tool to avoid crack on this area.

Due to the influence of the axial tension σ and the relation $Q/\mu P$ in the fretting fatigue process, experiments with different values of the axial tension σ, and the relation of the ratio $Q/\mu P$ has been carried out in order to evaluate the influence of each one of these parameters in the fretting fatigue life of the test specimens.

Table 4 shows fretting-fatigue results in different conditions. It will be probably very interesting to develop this study but some interesting comments can be already done with these results:

- SP type A shows the best improvement in fretting fatigue life. This process is able to multiply, at least, by 10 the life of the sample compared with as machined. This is also the process which create the most important roughness from 0.53µRa (As machined) to 6.37µRa (with SP type A). Friction coefficient is lower to the “as machined”. Both SP introduces the highest residual compressive stress magnitude and the nearest to the surface. This is probably of major importance to delay crack initiation.
- SP type B life is very similar to type 1 and processing this dual SP on this aluminium doesn’t improve the fretting-fatigue resistance.
- Concerning LP we are able to multiply, at least, by 3 the life the dog bone sample some other by 10 compared to the “as machined”. Then, the spread of life improvement is more important than SP. We can probably explain this by three results analysed in this study:
  - Even we can achieve a deeper compressive stress; we have got a lower residual compressive stress at the surface due to low cold working. It would be probably interesting to evaluate LP with 3 or 4 passes to increase a little bit cold working then optimise the surface residual stress. Then we could take the benefit of the maximum residual stress and deeper compressive stress.
  - We note also a lower roughness from LP than SP. Usually, it’s a great advantage to reduce roughness in fatigue condition but concerning fretting fatigue, it is very different. We need to increase roughness to reduce the coefficient of friction.
  - The contact point mark is not always circular like it should be with the spherical pad. That means we create higher tension on the contact point then we reduce the life of the sample. A contact with two planes would probably modify the results.
- LP + SP type A shows an improvement in life multiplied by 7 with a cracking initiation outside of the contact point. That means we can expect more and probably go back to the life with SP alone.

This demonstrates one more time the important effect of roughness to improve fretting-fatigue life associated with higher compressive residual stress at the surface.

Table 4
Life increasing/reduction with the maximum loading tested

	S(MPa)	QA(N)	QB(N)	P(N)	Cycles	Failure Location	Life reduction / increasing
Fatigue calculated	125	No	No	No	7.10^6	Reference without fretting For information.	
As machined	125	857	914	1000	65 614	contact	Divided by 107 Ref. with fretting
SP A	125	868	948	1000	947 249	edge	Multiplied by 14,4
SP B	125	861	907	1000	840 626	edge	Multiplied by 12,8
LP C	125	785	860	1000	249 289	contact	Multiplied by 3,8
LP C	125	895	910	1000	160 510	contact	Multiplied by 2,5
LP D	125	980	1005	1000	272 231	contact	Multiplied by 4,1
LP E	125	902	879	1000	169 597	contact	Multiplied by 2,6
LP F	125	900	900	1000	501 000	edge	Multiplied by 7,6

Conclusion

Evaluate the fretting fatigue behaviour on aluminium 7075-T651 with LP and SP is interesting but complex due to many variables we have to manage. One of the difficulties is the improvement so important from those processes that we need to take many precautions to the dog bone samples to initiate the crack at the contact point.

Nevertheless, it is possible to make the following conclusion in fretting-fatigue life under spherical contact conditions on this aluminium:

The first very positive comment is that a controlled SP, can multiply at least by 10 the life of the sample.
Increasing roughness from 0.53 µRa (as machined) to 6.37 µRa with SP is very beneficial to improve fretting fatigue life. Most of the SP samples fail outside of the contact point.
Concerning LP, we note a minimum increasing of life multiplied by 2.5 up to 10 according process and loading.
With LP finishing, the contact point mark from the pad is not always circular like it should be. This means we are not with the good condition of contact for fretting with the pad and we should have probably better results with two plane contacts instead of plane-spherical.
If we process SP after LP we go back to excellent results.
SP and LP are already used in the aircraft industry against fretting-fatigue cracking for many years but few results are published showing the effect of the different parameters of those processes. We hope these results will help engineers either to improve fretting fatigue behaviours of their components or investigate other configuration with fretting fatigue conditions.

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