ATTAINING FLAW-TOLERANT DESIGN LIFE OBJECTIVES IN HELICOPTER ROTOR SYSTEM LUGS

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Abstract

JAR 29 requires that flaw tolerance capabilities have to be demonstrated for fatigue assessment under paragraph 29.571. For lug sections, such as those commonly used in main and tail rotor assemblies of helicopters, this means tolerance from accidental damage in manufacturing and assembly, plus protection from fretting that can rapidly lead to fatigue crack initiation under dynamic rotor loading.

Most lug assemblies are bushed to provide a durable wear surface. Installation of ForceMate® bushes, which are radially expanded into lugs at a high interference, have been shown to provide significant fatigue and flaw tolerance life improvement over conventional bushing installation methods. In an extensive test program conducted jointly between Agusta, an AgustaWestland Company, and Fatigue Technology Inc., installation of ForceMate® bushes provided great benefit since the design target was achieved without reduction of design nominal stresses while simultaneously achieving a significant increase in safe life with induced artificial flaws.

Due to the major improvement in fatigue strength, an extensive test plan was carried out to validate the ForceMate® process, providing the relevant database for lugs in titanium and aluminum alloys used for mechanical lug assemblies. This test program involved tests on lug elements having minimum and maximum interference according to the allowable range in manufacturing standards. Tests compared undamaged (pristine) installations against flawed coupons containing artificially induced flaws prior to bushing installation.

The principle objectives of these tests were:

a. The evaluation of appropriate S-N curves and fatigue scatter, considering the allowable range of interference of the expanded bushings
b. Quantitative evaluation of the flaw tolerance capability

This paper will discuss the test objectives, a description of the ForceMate® bushing installation method and advantages, and present an overview of the results obtained when testing lugs representative of main and tail rotor assemblies with lugs manufactured from titanium Ti6Al4V Annealed alloy and Al 7475-T7351 alloy.

Introduction

Most lug assemblies are bushed to provide a durable wear surface. Installation of ForceMate® bushes, which are radially expanded into lugs at a high interference, have been shown to provide significant fatigue and flaw tolerance life improvement over conventional bushing installation methods.

Due to the major improvement in fatigue strength, an extensive test plan was carried out to validate the ForceMate® process, providing the relevant database for lugs in titanium and aluminum alloys used for mechanical lug assemblies. This test program involved tests on lug elements having minimum and maximum interference according to the allowable range in manufacturing standards. Tests compared

undamaged (pristine) installations against flawed coupons containing artificially induced flaws prior to bushing installation.

The principle objectives of these tests were the evaluation of:

a. appropriate S-N curves and fatigue scatter, considering the allowable range of interference of the expanded bushings;
b. flaw tolerance capability in terms of threshold to propagation of cracks, S-N curves and fatigue scatter;

For lugs representative of main and tail rotor assemblies manufactured from titanium Ti6Al4V Annealed alloy and Al 7475-T7351 alloy.

ForceMate® Bushing Installation

General Description

The ForceMate® system involves the cold expansion of an initially clearance fit bushing into a hole. A specially sized bushing, with a proprietary lubricant on the inside surface, is radially expanded into the hole by pulling a tapered expansion mandrel through the bushing as shown in Fig. 1. Both flanged and non-flanged bushings made, from most aerospace materials, can be installed.

The process of expanding the bushing will yield it into the hole creating a high interference fit. Depending on the combination between the relative modulus of the bushing material and the parent material, the installation process may also cold expand the surrounding material inducing beneficial residual compressive stresses in the lug. This combination of high interference fit and residual stresses effectively reduce the applied cyclic stress range at the hole resulting in significant increase in fatigue and crack growth life of lugs.

Advantages of ForceMate® Bushing Installation

In addition to the enhanced fatigue life, ForceMate provides a rapid, more consistent, and non-damaging bushing installation. The high interference fit will resist bushing rotation/migration, which could lead to fretting damage, and preclude the intrusion of corrosive agents at the bushing-to-hole interface. The initial clearance fit of the bushing prior to expansion also ensures the hole or the bushing protective coatings are not damaged during installation.

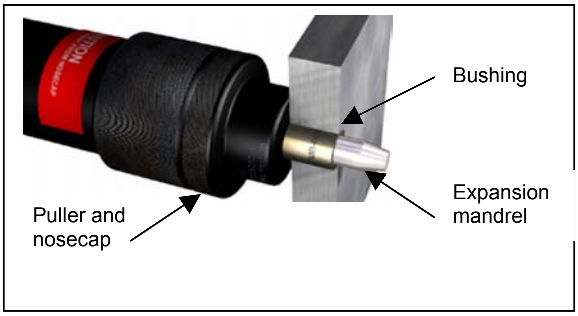


Fig. 1. ForceMate Bushing Installation

Test Specimens

The specimens, whose schematic view is shown in Fig. 2, were manufactured from Al 7475-T7351 bars and Ti6Al4V annealed forged plates. The starting hole diameter, bushing and tooling represented the maximum tolerances of the drawing and the required tooling sets. Two sets of dimensions were used representing typical Agusta main and tail rotor installations.

FTI designed the bushings and installation tooling for this program based on FTI FAN 735. The bushings were manufactured from 17-4 PH (H1025) stainless steel.

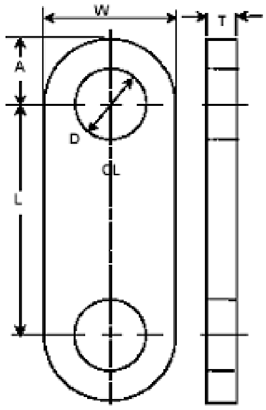


Fig. 2. Sketch of the specimens used for fatigue tests for both aluminum and titanium lugs

Test plan

Constant amplitude fatigue tests were performed using ASTM E466 as a guideline. The specimens were tested by load control Tests were performed in ambient lab air conditions. Table 1 summarizes the test programme activities.

The lug specimens were pin-loaded in clevis-type fixtures. After the breaking of the first lug (it's cut away), the test was continued with the lug pin-loaded in clevis-type fixtures mounted in hydraulic grip wedges, and other end of specimen gripped directly in hydraulic grip wedges.

Table 1. Global test programme activity carried out on ForceMate® bushing installation.

Material	Geometry	Interference level	Hole conditions	N° Tests
Al7475-T7351	MR	Min	Pristine	13
Al7475-T7351	MR	Min	0,15mm defect	5

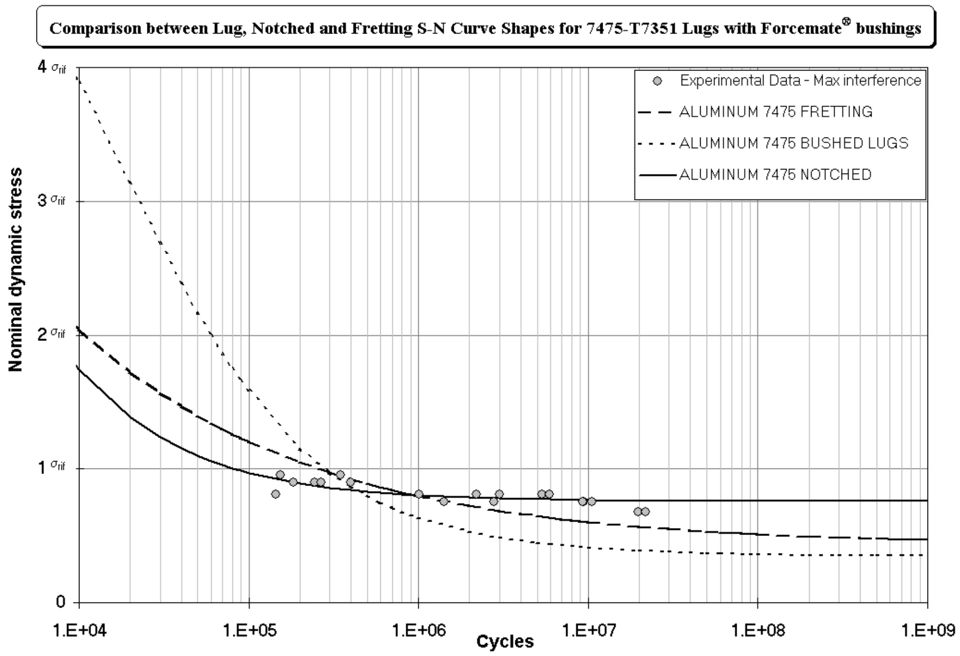
Al7475-T7351	MR	Min	0,25mm defect	5
Al7475-T7351	MR	Max	Pristine	20
Al7475-T7351	TR	Min	Pristine	9
Al7475-T7351	TR	Min	0,15mm defect	4
Al7475-T7351	TR	Min	0,25mm defect	4
Ti6Al4V	MR	Min	Pristine	16
Ti6Al4V	MR	Min	0,15mm defect	12
Ti6Al4V	MR	Min	0,25mm defect	12
Ti6Al4V	MR	Max	Pristine	18
Ti6Al4V	TR	Min	Pristine	14

Test Results

7475-T7351 Aluminium Lugs

Pristine Lugs. A series of fatigue tests have been carried out on specimens representative of main and tail rotor installation with both maximum and minimum interference level foreseen for this application.

Absence of fretting was shown for both interference levels which also showed the same trend in terms of S/N curve shape, which is the typical for aluminum alloys 7475 notched (See Fig. 3).



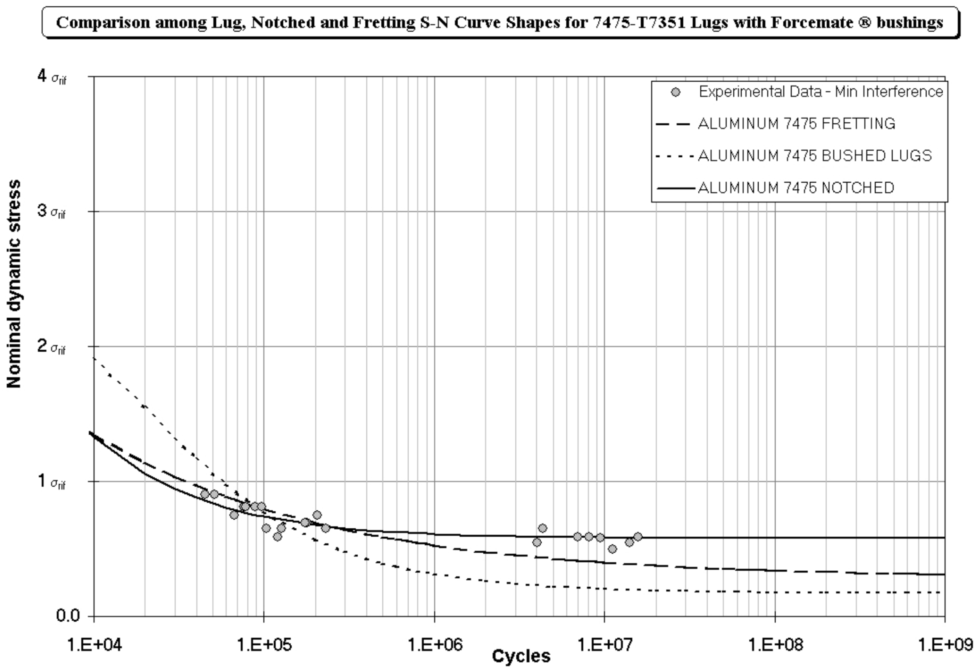


Fig. 3. The S/N curve shape that better describes the fatigue behavior of the ForceMate® bushing installation is the typical for aluminum alloys 7475 notched.

The interference level anyway strongly affects the fatigue limit, showing a scatter of 30% between the two levels (See Fig. 4).

Fig. 4 also shows that, despite this scatter, the absence of fretting is extremely favourable in terms of fatigue strength so that the fatigue allowables with ForceMate® bushings installed are much bigger than those found for bushed lugs at high interference level.

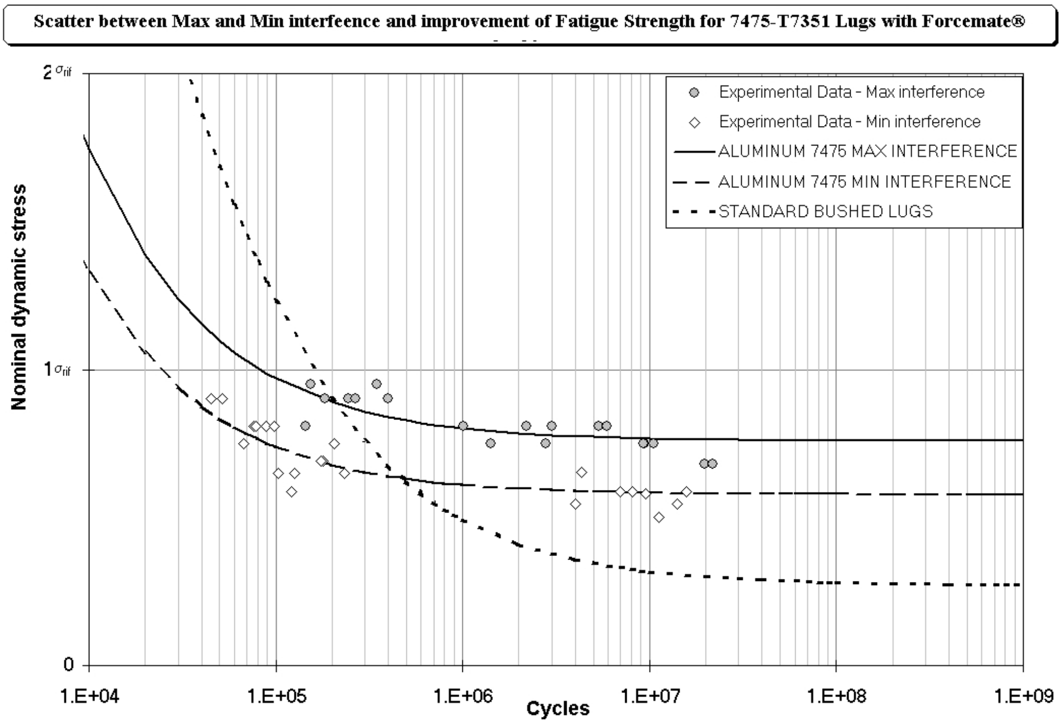


Fig. 4. The interference level strongly affects the fatigue strength of the ForceMate® bushing installation. The scatter between the two levels is 30%.

<u>Flawed lugs.</u> In order to characterize the fatigue behavior in presence of micro defects or cracks, a series of tests have been carried out on lugs with quarter circular corner cracks 0,15 and 0,25mm deep artificially produced on the lugs before the installations of the bushing. These defect sizes allowed to properly build the Kitagawa <u>plots, which have the aim to provide the threshold stresses to propagation of small cracks with varying the stress ratio and the crack size.</u>

No other damage is possible after the installation. They have been produced by electrical discharge machining, which has the characteristics to leave their surface, when analyzed with S.E.M., rough, rich with micro-cracks, especially at the bottom, and without residual stresses (see Fig. 5).

The tests showed that fatigue behavior of cracked lugs is strongly affected by the presence of the crack. An explanation of this detrimental effect of the crack is that the beneficial effect of the residual compressive stresses is big during the crack nucleation/small crack phase but much lower during the crack propagation. This is also confirmed by the small fatigue strength reduction between the two crack sizes. The difference can be addressed only to the number of loading cycles to propagate from 0,15mm up to 0,25mm.

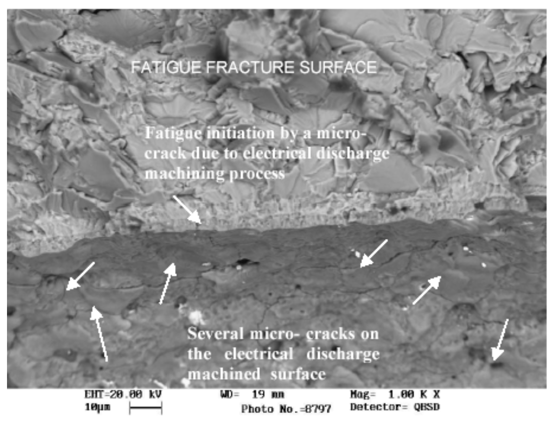


Fig. 5. S.E.M. view of the several micro cracks on the surface of the flaws obtained by electrical discharge machining

Moreover, whilst the typical S/N curve shape of aluminum 7475 alloy notched describes the fatigue behavior of the pristine specimens, the one of the flawed specimens is described by a best-fit curve similar to the fretting. This is reasonable when considering the fatigue process a combination of a nucleation phase (the large amount of the time) and a propagation phase. When fretting is present, the time spent in the nucleation phase is considerably reduced if not completely absent.

Fig. 6 shows the comparison between the fatigue strengths of pristine and flawed specimens (minimum interference level) as well as the different shape of the S/N curve representing their behavior.

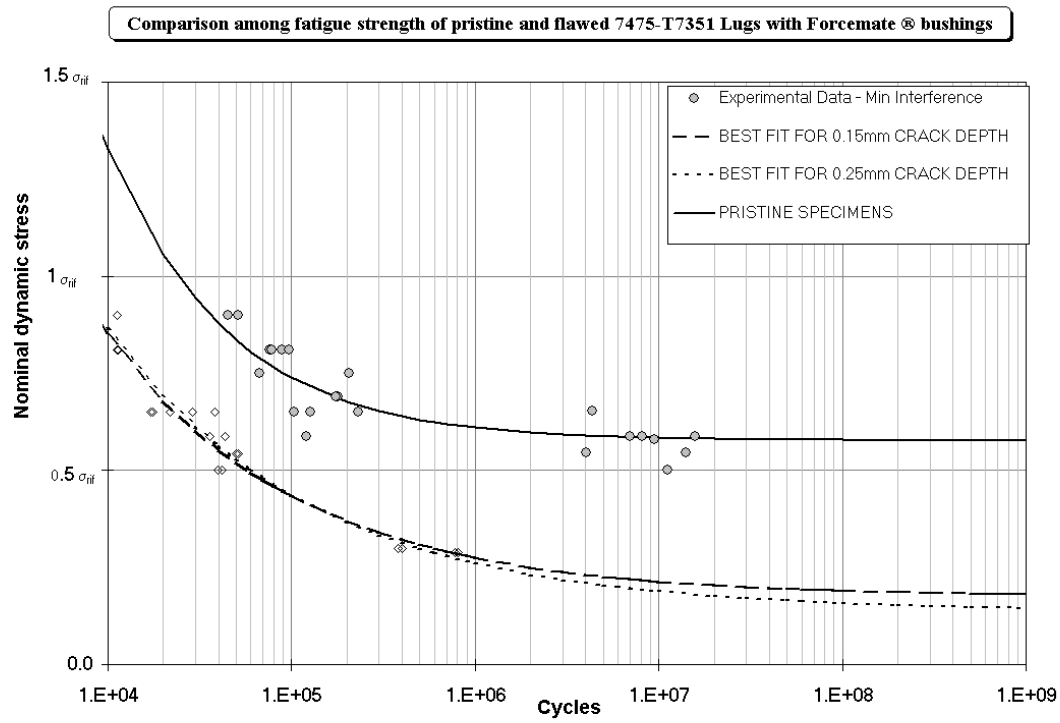


Fig. 6. The fatigue behavior of the ForceMate® bushing installation is strongly affected by the presence of small cracks

Ti6Al4V Titanium Lugs

Pristine Lugs. A series of fatigue tests have been carried out on specimens representative of main and tail rotor installation with both maximum and minimum interference level foreseen for this application.

Also for titanium lugs absence of fretting was shown for both interference levels but in this case no standard S/N curve shape is able to properly represent the fatigue behavior of this installation.

Another and more important difference with respect to the aluminum lugs is represented by the insensitivity to range of interference level both in terms of fatigue limit and S/N curve shape.

A further difference with respect to the aluminum lugs is represented by the substantially lack of improvement of the fatigue limit with respect to the one found for bushed lugs at high interference level (dashed line on Fig. 7), which also showed absence of fretting. The benefit of this kind of installation is nevertheless effective for higher loads (in the range 10^5 – 10^7 cycles, see always Fig. 6). This benefit could be due to better protection against fretting up to these higher loads.

Fig. 7 shows the fatigue behavior of the ForceMate® bushings installed on titanium lugs compared with the one related to the typical bushing installations (high interference level).

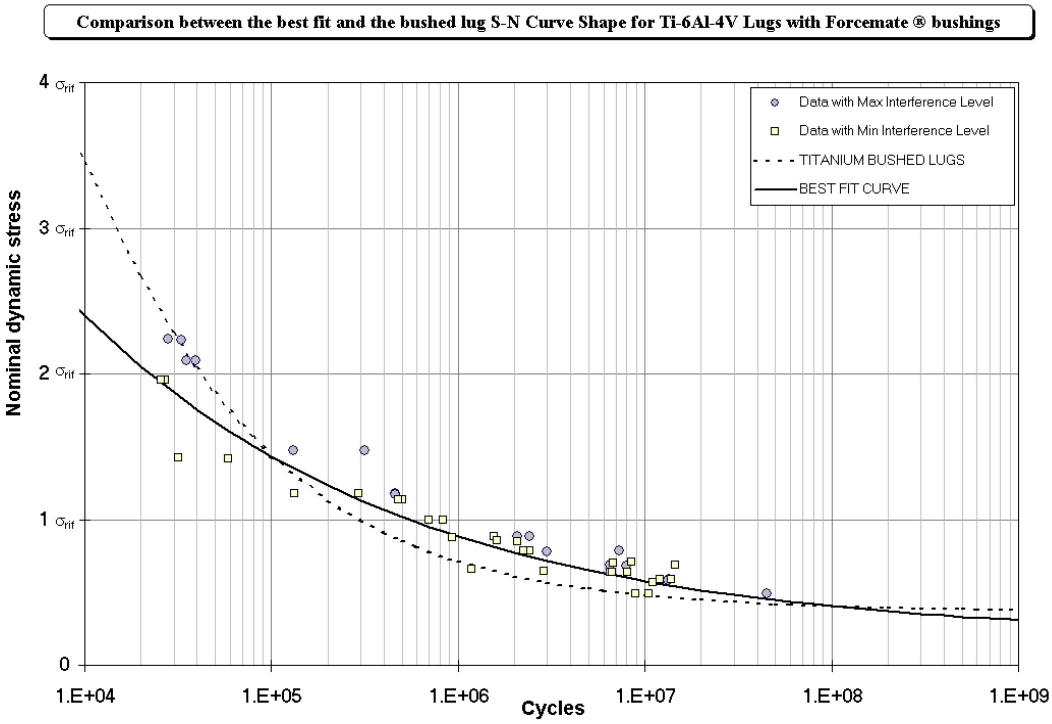


Fig. 7. The fatigue behavior of the ForceMate® bushing installation in the titanium lugs is not significantly influenced by the range of interference level.

Flawed Lugs. In order to characterize the fatigue behavior in presence of micro defects or cracks, a series of tests have been carried out on lugs with quarter circular corner cracks 0,15 and 0,25mm deep artificially produced on the lugs before the installations of the bushing. These defect sizes allowed to properly build the Kitagawa plots which have the aim to provide the threshold stresses to propagation of small cracks with varying the stress ratio and the crack size.

No other damage is possible after the installation. They have been produced by electrical discharge machining, which has the characteristics to leave their surface, when analyzed with S.E.M., rough, rich with micro-cracks, especially at the bottom, and without residual stresses (see Fig. 5).

The tests showed that fatigue behavior of cracked lugs is strongly affected by the presence of the crack. An explanation of this detrimental effect of the crack is that the beneficial effect of the residual compressive stresses is big during the crack nucleation phase but much lower during the crack propagation.

This is also confirmed by the very small fatigue strength reduction between the two crack sizes. The difference can be addressed only to the number of loading cycles to propagate from 0,15mm up to 0,25mm.

The behavior of the flawed specimens is described by a best fit curve which is quite similar to the fretting (even though less than for aluminum lugs). This is reasonable when considering the fatigue process a combination of a nucleation phase (the large amount of the time) and a propagation phase. When fretting is present, the time spent in the nucleation phase is considerably reduced if not completely absent.

Fig. 8 shows the comparison between the fatigue strengths of pristine and flawed specimens (minimum interference level).

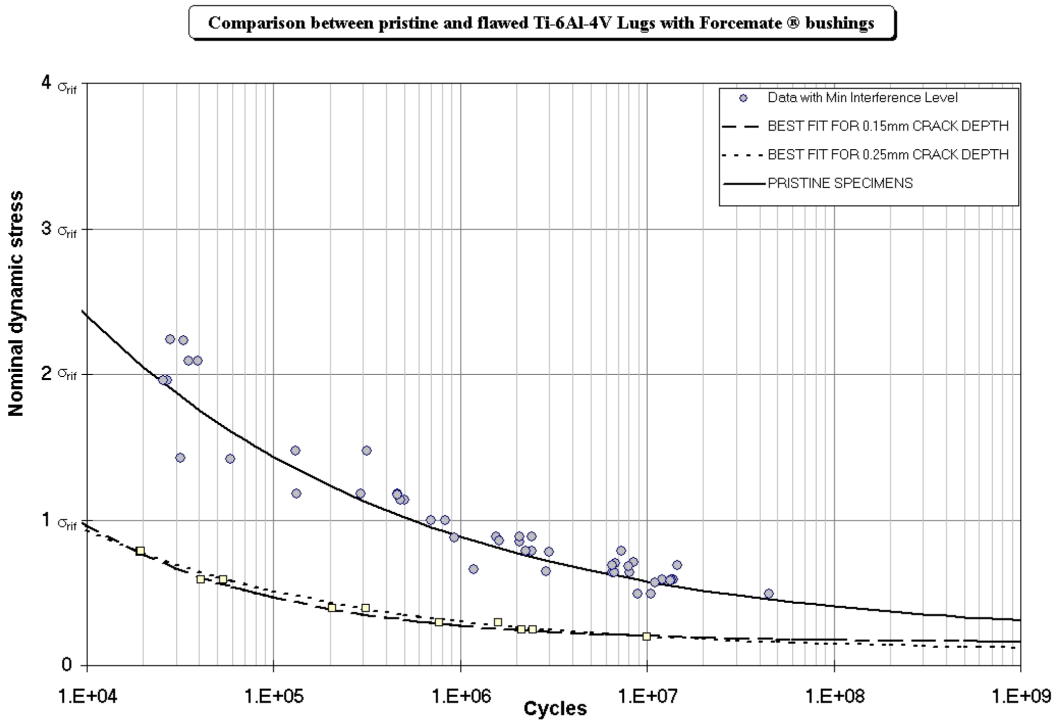


Fig. 8. The fatigue behavior of the ForceMate® bushing installation is strongly affected by the presence of small cracks which can reduce the fatigue strength of the pristine specimens by more than 2 times.

Flaw Tolerance Capabilities

The tests carried out on flawed specimens allowed to build the Kitagawa plots for both the aluminum and titanium lugs that have the aim to provide the threshold stresses to propagation of small cracks with varying the stress ratio and the crack size. These plots allow also to calculate the knockdown factors between the fatigue allowable of pristine specimens and the one of flawed specimens (in this key the fatigue allowables are to seen as threshold to propagation). On the other side, given a knockdown factor, it is possible to calculate the maximum crack size, which does not propagate if the stress applied is equal to the fatigue allowable, reduced by that factor.

On the basis of this statement it is possible to calculate the maximum crack size covered by the safety factors used for safe life calculation. The crack sizes covered by the safe life analysis for aluminum and titanium lug provided by ForceMate® bushings installation are 0,05 and 0,07mm respectively.

Figs. 9a and 9b shows the Kitagawa plots calculated for these two materials.

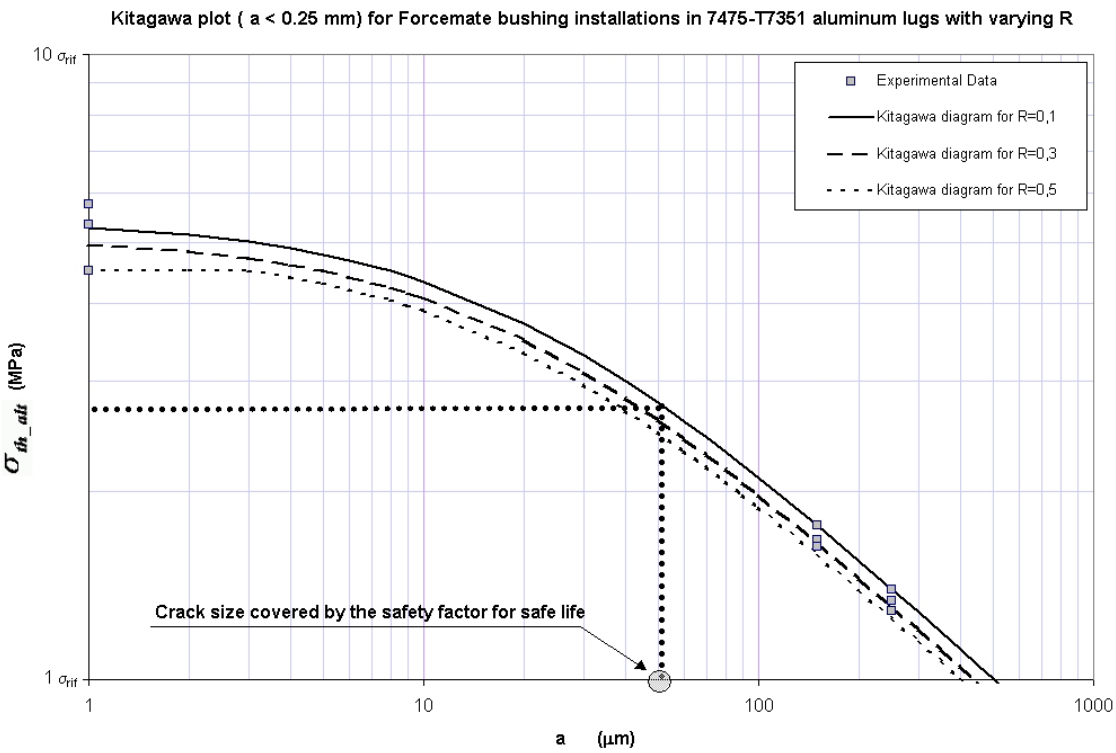


Fig. 9a. The tests carried out on flawed specimens allowed to build the Kitagawa plot with varying the stress ratio.

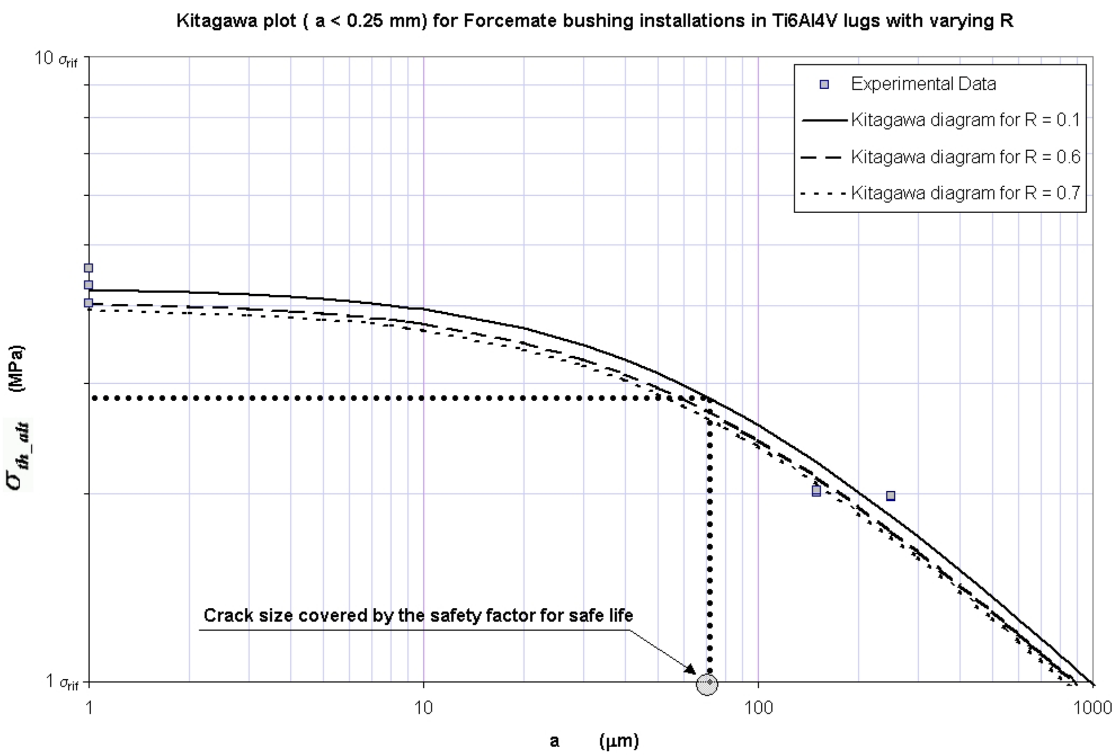


Fig. 9b. The tests carried out on flawed specimens allowed to build the Kitagawa plot with varying the stress ratio.

Conclusion

Most lug assemblies are bushed to provide a durable wear surface. Installation of ForceMate® bushes, which are radially expanded into lugs at a high interference, have been shown to provide significant fatigue and flaw tolerance life improvement over conventional bushing installation methods.
An extensive test plan was carried out to validate the ForceMate process, providing the relevant database for lugs in titanium and aluminum alloys used for mechanical lug assemblies. This test program involved tests on lug elements having minimum and maximum interference according to the allowable range in manufacturing standards. Tests compared undamaged (pristine) installations against flawed coupons containing artificially induced flaws prior to bushing installation.

The principle objectives of these tests were the evaluation of:

a. Appropriate S-N curves and fatigue scatter, considering the allowable range of interference of the expanded bushings.
b. Flaw tolerance capability in terms of threshold to propagation of cracks, S-N curves and fatigue scatter.

After the completion of the test activity, the following conclusions can be drawn:

7475-T7351 Aluminium Lugs

Pristine Specimens:

1. The behavior of these lugs is strongly dependent on the interference level; a factor 1,30 between the min (worse) and the max values can be found.
2. The behavior of these lugs is well characterized by a notched S/N curve shape, being the bushings able to avoid fretting.
3. The fatigue allowable is much bigger than the one calculated for bushed lugs with high interference.

Flawed Specimens:

1. Two defects have been investigated, quarter circular corner flaws 0,15 and 0,25mm deep. Using the Electrical Discharge Machining method so they are considered to be like cracks has produced them.
2. The behavior of these lugs is well characterized by a best-fit curve; no standard S/N curve is able to properly describe their behavior.
3. It is possible to draw a Kitagawa diagram that allows calculating the crack size (depth of a quarter-circular corner crack) covered by the safety factor for safe life that is 0,05mm.

Ti6Al4V Titanium Lugs

Pristine Specimens:

1. The behavior of these lugs is not dependent on the interference level.
2. The behavior of these lugs is well characterized by a best-fit curve; no standard S/N curve is able to properly describe their behavior.
3. The fatigue allowables calculated for this installation are very close to those calculated for bushed lugs with high interference.

Flawed Specimens:

1. Two defects have been investigated, quarter circular corner flaws 0,15 and 0,25mm deep. They have been produced by using the Electrical Discharge Machining method so they are considered to be like cracks.
2. The behavior of these lugs is well characterized by a best-fit curve; no standard S/N curve is able to properly describe their behavior.
3. It is possible to draw a Kitagawa diagram that allows calculating the crack size (depth of a quarter-circular corner crack) covered by the safety factor for safe life, which is 0,07mm.

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