Simulation of residual stresses due to cold-expansion bushing installations. Application to Fatigue Life Evaluation.

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The cold expansion processes have been used for many years in the aeronautical industry in order to improve the fatigue life of structural components. The physical phenomenon underlining such improvement is well understood, however there is still not a recognized general method to provide accurate estimations for each specific problem. This work presents an attempt by Airbus Military (AIM) to develop a methodology based on analytical procedures in order to estimate the crack initiation in big aluminium alloy lugs fitted with bronze cold expanded bushings from Fatigue Technology Inc. This technique produces beneficial high compressive residual stresses which have been predicted by means of finite element models, both in 2D and in 3D for proper assessment of thickness effects. Finite element models have been developed increasing their complexity, step by step, while different evaluations of their capabilities were performed. Some test measurements have also been performed in real specimens in order to validate the FEM. The fatigue life predictions have been correlated with test results of specimens manufactured with different bushing installation procedures – non-interference, cryogenic shrink-fit and cold expanded - and loaded with constant and variable amplitude spectra, representative of in service usage. These tests, which highlight a significant benefit of this technology for large diameter lugs, show a reasonable accuracy of the developed methodology for preliminary assessments. Subsequent validation has led to significant savings in design and certification costs of AIM big fittings design.

Keywords: Lug, Fatigue, Cold-expansion, Residual Stress

1. Introduction

Fatigue life and damage tolerance evaluation of aeronautic structures is an essential design factor for its dual involvement in safety (certification requirements) and economics (to avoid the presence of cracks and subsequent repairs). These considerations lead to the need of implementing structural configurations that maximize the fatigue life of parts with minimal impact on weight and cost.

During the design phase of an aircraft landing gear, a fatigue limitation is identified in the lugs of the main fitting. From a fatigue point of view this part is critical due to the slow turn operations on ground, which basically introduce axial loads on the lugs with opposite directions at both sides of the part. This type of loading contributes to the development of significant bending stresses on the lugs, and a fatigue critical location at the intersection of the inner hole with the external surface, perpendicular to the applied load direction.

1.1 Certification Issues

The landing gear structure is classified as safe-life, certified under CS 25.571 by means of analysis supported by tests. The industry involved in the design has developed analytical procedures supported by tests for the fatigue assessment of the structure, generally accepted by the certification authorities.

These tests, although required for certification, involve important costs and can have an impact on the development schedule. As a result some guaranties of the success of the test campaign would be desirable in order to obtain the approval of such task. These guaranties can only be obtained with comparison with previous similar data and/or through analytical assessment.

1.2 Design improvements

The part under consideration is manufactured from forged 7010-T74 aluminium. In the baseline design bronze bushings are installed in the lugs using the cryogenic shrink-fit procedure. Several design alternatives were evaluated to solve the fatigue issue:

- Reinforcement of the lug area by increasing its dimensions. This solution gives a very limited improvement due to the high constraints of this type of structure, which must be allocated in a small space and comply with multiple system requirements such as the extension and retraction operations.
- Material change:
  - Using titanium introduces a significant cost increase and slight weight increment.
  - If steel were used there would be a very important weight increment of the whole part in order to keep the required strength and stiffness for the part to comply with its structural requirements.
- Pin reinforcement. The selection of high strength steel hollow pins allows them to be designed with a relatively thin wall to sustain the required static loads. However, because the thickness reduction deformations of the pin will be higher. It has been shown that the pin deformation can contribute in some amount to the stress concentration factor in the aluminium lug, but the benefit was small compared to the weight increase in this particular location.
- Bushing installation modification. Another alternative to improve the fatigue life of lugs is the installation of cold-expanded high interference bushings. The problem of this solution is that there is not a generally accepted analytical procedure for the assessment of the fatigue beneficial effect.

The final design incorporates a local redesign, pin reinforcement and cold-expanded bushings installation. Among them, the last one has been shown to be the most effective one so this work has been prepared to assess a specific application of the cold-expanded technology, the Force-Mate (Fatigue Technology Inc)

2. Scope

The scope of this work is to obtain a methodology to estimate the beneficial effect of the high compressive residual stresses originated after the cold expanded bushing installation.

Fatigue life predictions have been performed in three different configurations in order to compare resulting life improvement (clearance-fit bushing, shrink-fit bushing and cold-expanded bushing).

2.1 Methodology

The following steps have been considered for the fatigue assessment:

- Residual stresses evaluation. Studies were made in order to understand the residual stresses introduced after bushing installations, specially focused on the study of cold expanded installations
- Stress concentration factor assessment. Through the modelling of loading process, stress concentration has been evaluated in the critical areas.
- Fatigue life calculation. Two different approaches have been followed in order to evaluate the improvements of the different techniques:
    - Stress-life approach
    - Strain-life approach

2.2 Test Campaign

A limited set of fatigue tests have been performed by AIM in order to validate the developed methodology. During the test, the three bushing configurations mentioned before were tested in a simplified version of the real geometry.

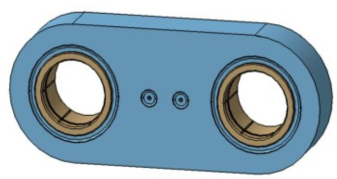


Fig. 1 - Test specimen

The specimen for the test is a simplified version of the actual geometry, where the general stress behaviour is reproduced. The specimen is made of Al 7050-T7451 Plate, with a raw thickness between 75 and 80 mm, finally machined to 65 mm. The inner lug radius is 105 mm and the outer radius is 202 mm. The element is protected with chromic anodizing and a primer

Fig. 2 - Test machine

Fig. 3 - Specimen failure section

Constant and variable amplitude load spectra have been tested at AIM facilities, in a Universal Test Machine (UTM) with a capacity of 500Tn (5,000kN). The load application is only in tension, which avoids the problems of possible buckling, and is considered adequate for the assessment of the fatigue behaviour of lugs under axial load. Applied load has an offset with the specimen centreline in order to simulate the bending stress in the actual part.

Spectrum	Configuration	Stress level (Tn)	R ratio	No. Specimens
Variable	Force-Mate	--	–	5
	Clearance-Fit		–	3
Constant	Force-Mate	74	0.1	3
		54	0.1	2
	Shrink-Fit	74	0.1	3
		54	0.1	3
	Clearance-Fit	84	0.1	3
			0.5	3
		74	0.1	4
			0.5	3
		54	0.1	3
		64	0.5	3

2.3 Cold-expanded bushings installation

In the cold expanded bushings, the outer diameter of the bushing is slightly smaller than the inner diameter of the lug. It is installed in the lug, and then expanded at room temperature with a mandrel that has an external diameter bigger than the bushing inner one, creating a high interference with the lug.

The following figure shows the bushing installation in a test specimen, and the movement of the mandrel through the hole.

Fig. 4 –Cold expanded bushing installation process

3. Residual stresses evaluation

In the first place, analytic studies on the residual stresses originated in the lug after the bushing installation have been performed. Once the phenomena has been well understood, studies on the effect of some parameters has been performed obtaining useful information to define the Finite Element Models (FEMs) finally used. Simulations have been performed with 2D and 3D Abaqus/Std FEMs in order to evaluate the residual stresses.

Finally a comparison will be made with experimental measurements of the residual stresses by the hole drilling method and the proper conclusions will be extracted.

3.1 Analytical approach and preliminary assessments

Contact and plastic behaviour simulation capabilities of the FEMs have been evaluated by comparison with analytic solutions.

3.1.1 Plastic strain evaluation

An analytic solution for a tube expansion under internal pressure has been performed. Hypothesis used are axysimmetric geometry and plane-strain perfect-plastic behaviour (without material hardening). Plastic strain has been obtained by the Prandtl-Reuss equations and the Von Mises yield criteria.

The analytic solution has been compared with a quarter circle FEM developed with the same hypothesis. The minimum mesh density and element order have been chosen looking for a compromise of accuracy and low CPU time consumption. The best performance has been obtained for a mesh of 2nd order quad elements, one for each 2.5º of the circle (144 elements around the hole).

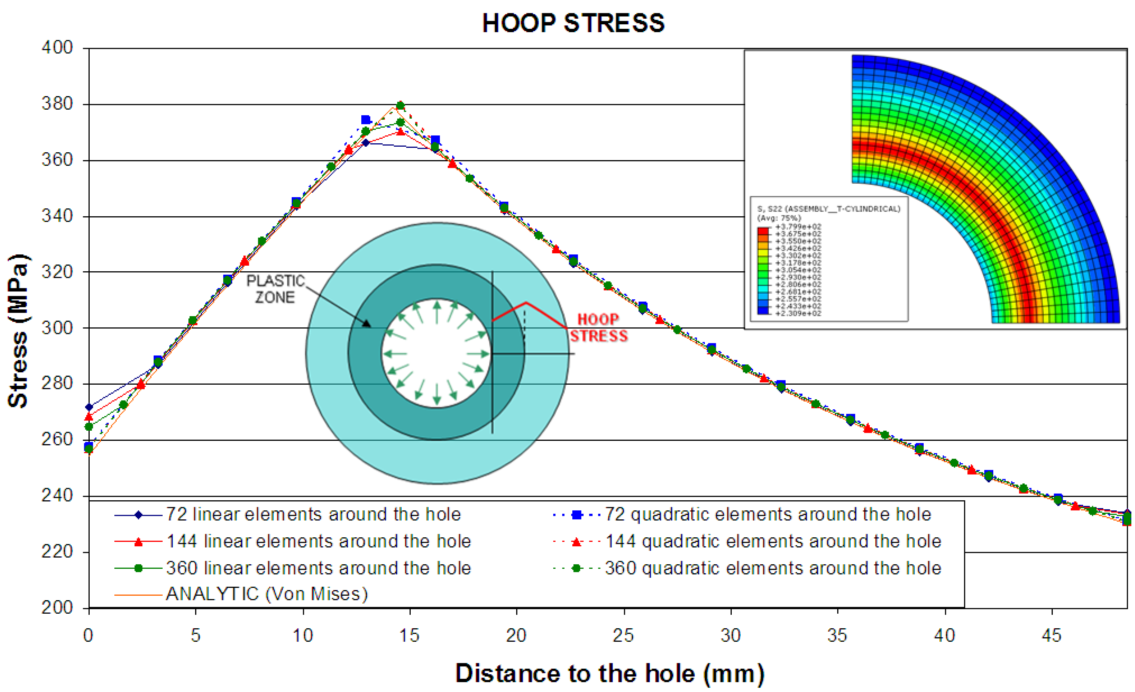


Fig. 5 - Hoop stress of a tube under internal pressure

3.1.2 Contact representation capabilities

In the same way that has been done for the plastic strain evaluation, an analytic solution for a shrink fit has been performed. Hypothesis used are axysimmetric geometry and plane-strain elastic behaviour.

The analytic solution has been compared with a FEM circle with the mesh already defined validating this configuration for the upcoming work.

3.1.3 Analytical solutions limitations

An analytic solution of the full installation process has been developed. Unfortunately it couldn't be used for a proper future fatigue calculation for the following reasons:

- Plastic hardening behaviour: the stress distribution changes when this behaviour is introduced becoming curved instead of sharp evolution (see Fig. 6)
- Real shape introduction (non axysimmetric).
- Load process representation, which is imperative for this work

For these reasons, a finite element model has been developed.

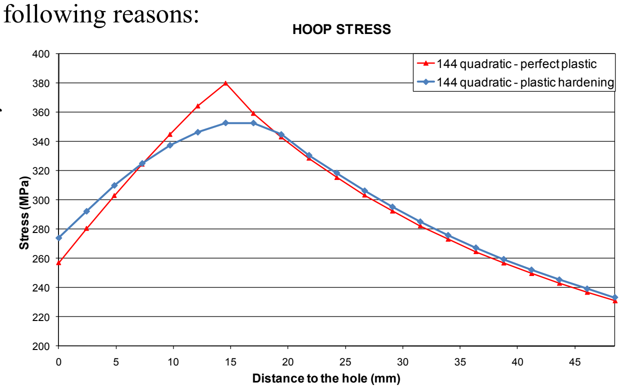


Fig. 6 - Plastic hardening introduction

3.2 2D finite element models

Although the problem is essentially three-dimensional, a 2D model allows the assessment of the effect of some parameters in a reasonable amount of time, and a comparison with the more complex and time consuming 3D model will validate 2D FE results.

Abaqus/Std

2-D plane strain FEM simulations of the test specimen have been used to evaluate the residual stresses after bushing installation of both shrink-fit and cold-expanded bushing configurations. It is also used for sensitivity assessment of several aspects of the problem, such as boundary conditions, material behaviour definition, and load application process.

<u>Analysis of shrink-fit</u>

The shrink-fit simulation of the bushing installation is performed by defining a bushing outer diameter that is slightly bigger than the lug inner diameter, and the Abaqus method of surfaces adjustment when the contact between them is defined.

<u>Analysis of cold-expansion</u>

The cold expansion process has been divided into two steps during simulation:

- Expansion: uniform radial displacements on the inner diameter of the bushing are introduced to simulate the cold expansion. This step simulates the axial movement of the mandrel through the specimen thickness.
- Relaxation: the removal of the mandrel and the corresponding unloading process is simulated by the removal of the previously introduced boundary condition at the bushing inner diameter.

<u>Contact definitions</u>

In Abaqus FEM, contacts between lug and bushing, and between bushing and pin, have been defined as surface to surface tangential behaviour without friction, small sliding formulation. Bushing faces are used as slave surfaces in both cases. Surfaces of lug and bushing are adjusted to remove overclosure at the beginning of the simulation.

Mesh

Due to the symmetry in geometry and load, only a quarter of the specimen is modelled, with the proper symmetrical boundary conditions. A plane strain quadratic elements distribution obtained in point 3.1.1 is used (CPE8R). Because of the symmetry, the number of elements around the semi lug hole is 72.

Material

Bronze (bushing) and aluminium (lug) have been introduced as elasto-plastic materials while steel (pin) has been modelled as purely elastic. Although assessments have been made on a kinematic hardening behaviour, an isotropic hardening model has been used.

The properties for 7050-T7451 aluminium lug are taken from Ref. 1, with Ramber-Osgood formulation for the strain-stress curve.

E = 71020 MPa, Fty = 455.1 MPa, n = 19

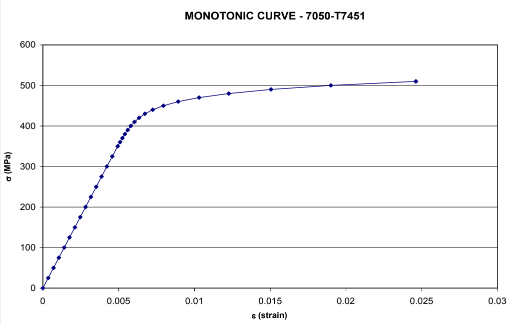


Fig. 7 - Aluminium stress – strain curve

The properties for the bronze bushing are taken from commercial information, using also the Ramber-Osgood formulation.

E = 120663 MPa, Fty = 345 MPa, n = 5.64

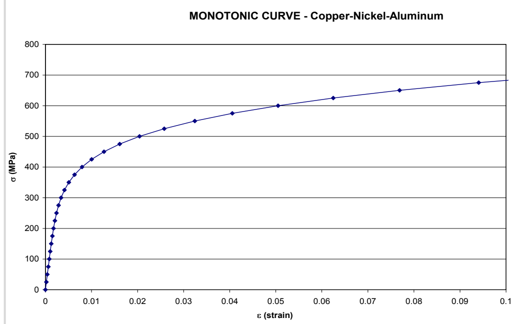


Fig. 8 - Bronze stress – strain curve

For the subsequent load application process, the properties for the 4340 steel pin are just the elastic ones.

E = 200000 MPa

Results

The following plots show the hoop stresses at the end of the expansion step and the relaxation step.

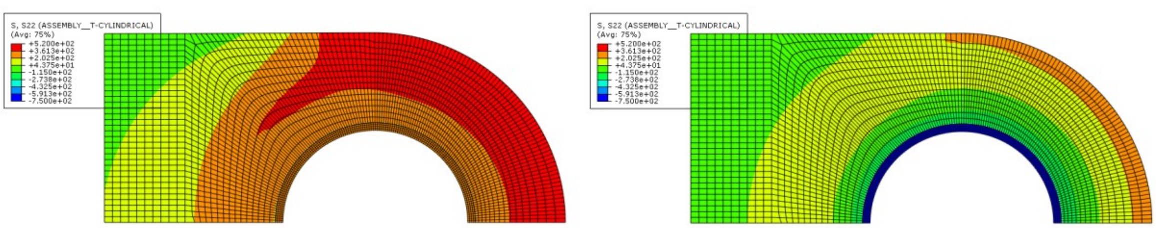


Fig. 9 – Expansion and relaxation steps

3.3 3D finite element models

3-D FEM simulations have been used to evaluate the mandrel pull-through during the cold expansion process. In this case the axial movement of the mandrel through the specimen has been introduced in the model to obtain the distribution of the residual stresses through the thickness. 3D load application by the pin has also been modelled making possible to evaluate the stress-bending effect.

Due to its complexity, high memory requirements and long CPU time are needed in order to run this kind of 3D FEM.

However, the specimen geometry has been simplified and a higher quality mesh was created refining element sizes only in the areas closest to the hole in order to reduce required CPU time machine.

Material definitions for lug, bushing and mandrel are the same already used for the 2D FEM models. The mandrel has been modelled as an analytical rigid body so it was not necessary to define a mesh or material behaviour for this part.

Abaqus/Std

Analysis

Some new steps not present in the 2D model were introduced:

- Steps 1 & 2: bushing contact with the lug is achieved (first the flange and then the cylindrical face).
- Steps 3 & 4 hole expansion: mandrel movement through the bushing hole introduce cold expansion. During these steps, the lower face of the lug leans on the puller machine; this has been represented as a boundary condition (a special study has been made to verify that puller stiffness introduction does not improve FEM results).
- Additional boundary conditions are released.

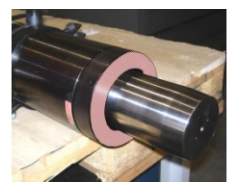


Fig. 10 – Puller contact area

Contact definitions

Some changes have been made on the 2D FEM contact definitions to adapt to the 3D FEM:

- Lug to bushing contact has been divided in two areas: the cylindrical body and the flange. Friction coefficient of 0.1 has been introduced in order to improve convergence.
- The pin and the mandrel only make contact on the inner surface of the bushing.

Mesh

Because of the symmetry, half of the lug is representative of the entire specimen. The 8-node brick C3D8R 3D element has been adopted for the analysis. The analysis model contains the following element and nodes:

	PART INSTANCE		
	Bushing	Lug	Pin
ELEMENTS	42768	48770	42768
NODES	54520	54433	54520

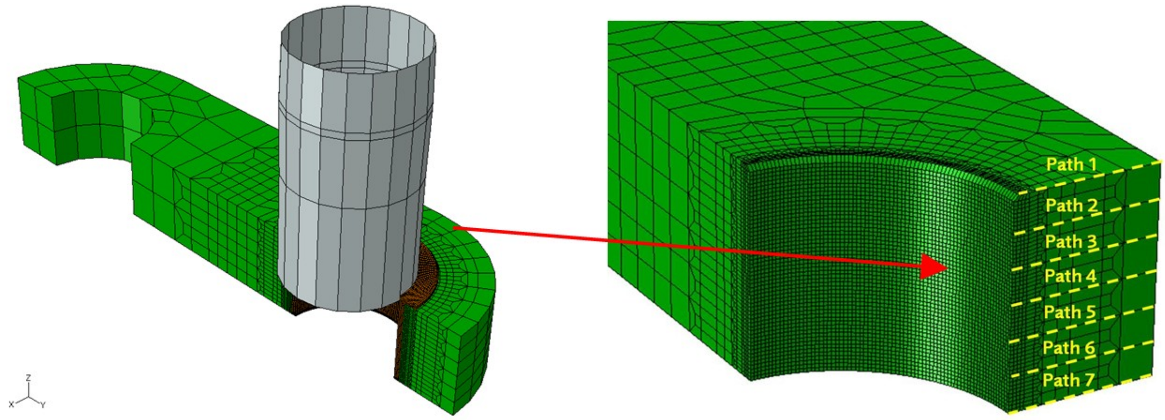


Fig. 11 - 3D FEM mesh, with mandrel for cold-expansion and fatigue critical section

3.4 Residual stress measurement

An attempt has been made to measure the residual stresses after the cold-expanded bushing installation in order to support the FEM model results. A couple of testing methods were evaluated, such as the neutron diffraction and the hole-drilling method. Although the first one was technically preferred, finally the hole-drilling method was selected due to project constraints.

Due to budget and time constraints, it was not possible to perform any measurement on the specimens before being tested. It is assumed that the test can influence the residual stress field in the lug. This possibility makes the correlation with the FEM more difficult, but in some way takes into account the possible effect of the spectrum application in the residual stress field. For that purpose, measurements are made on parts which have been tested under different spectra.

The test specimens have two lugs, and usually only one of them has failed in the test. The specimens for residual stress measurement are selected such that the other lug (in which measurements are made) presents no damage.

In this hole-drilling method, several strain gauges are bonded on the surface of the part, and then a small hole is drilled close to them. The stress relaxation produced after drilling the hole is an indication of the residual stress field.

The calculation of the residual stresses from the gauges strain measurements has been performed according to Ref. 3.

Fig. 12 - Hole-drilling tool and drilling operation

3.5 Results

The following plot shows a comparison between the measured residual stresses and the calculated ones from both 2D and 3D FEM models (paths defined in Fig. 11):

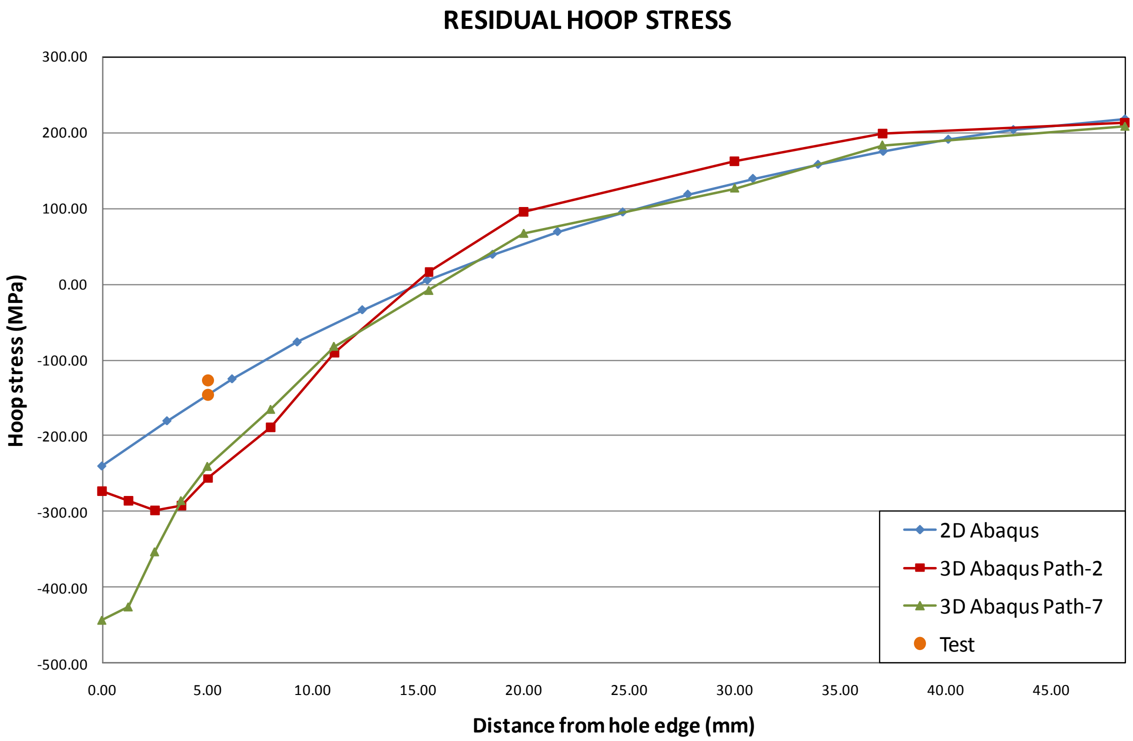


Fig. 13 - Residual stress measurement vs prediction

The tested specimens have shown that the critical location at which cracks start is located at some depth from the surface of the lug (see Fig. 2).

In the above plot the good match of the measurement and the 2D prediction could be a coincidence, but it is a indication that the calculated residual stresses at the lug hole are reasonable.

Worth nothing is the fact that an evaluation of the possible variation of the residual stresses with depth, and the associated correction of the measurements, has not been carried out in this job. It too has to be pointed out that deviations in the measured strain relaxations appear due to localized yielding at the stress concentration created by the presence of the hole (common when residual stresses exceed about 50 percent of the yield stress, which is the case in these lugs). Additionally the fact that the measurements have been performed after the specimens have been tested could have an influence on the residual stresses. In this sense, further investigation is required for a proper correlation between measurements and 3D FEM prediction.

4. Fatigue life calculation

The critical location in the lug under axial loading would be at the lug hole in a perpendicular direction to the load application line, as verified in the tests initiation location (Fig. 2).

The fatigue assessment (crack initiation) of the lug specimen under the spectrum loading is made using the typical AIM analytical tools. Basically the procedure involves the evaluation of a stress concentration factor (Kt), the selection of proper S-N material data, and the application of the Miner's rule for damage accumulation.

Most of the fatigue analyses performed in AIM use the stress-life approach. The cold-expanded technique involves important material plastic effects, so the strain-life approach will be also evaluated. This is part of a more general AIM program of fatigue evaluation under residual stresses using the strain-life approach, such as those produced during in-service overload events. Since one of the objectives is using typical company procedures, the fatigue material properties will be taken from AIM databases, and no specific material characterization is made.

The standard AIM procedure for calculating the fatigue life consists on a development of the spectrum in terms of a reference stress (net stress), and a calculation of a Kt combined with an adequate S-N curve (obtained from plain specimens with notches simulating the Kt) and Miner's rule. In this particular application, since the cold-expansion process affects the local stresses at the critical location, it is more suitable to work directly with those local stresses rather than a reference stress.

In all cases, the stress concentration factor is calculated as

$Kt = \Delta\sigma_{notch} / \sigma_{ref}$ where:

– $\Delta\sigma_{notch}$ is the increment between the notch stress after load application and the notch stress in the initial residual stress field.

– σ_{ref} is the lug net stress.

For a fatigue evaluation of the lug with the different bushings configurations, it is necessary to consider those aspects of the bushing installation that have an effect on the fatigue behaviour. Next figures describe the notch stresses for each of the configurations tested.

CLEARANCE-FIT

When the bushings are installed with clearance-fit, the notch stresses at the critical location would be approximately proportional to the applied loading. In this configuration high fretting effects are anticipated which reduces the fatigue life.

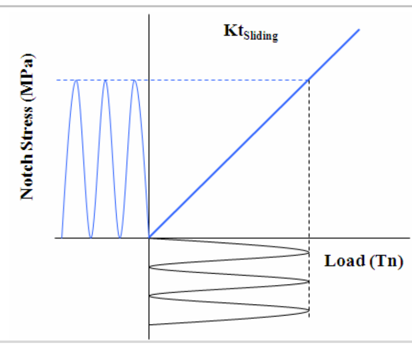
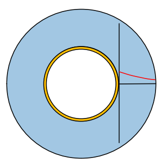


Fig. 14 - Local stress in clearance-fit

In the lug configuration with cryogenic shrink-fit bushings, the usual practice assumes no bushing interference for the Kt evaluation.



SHRINK-FIT

In the shrink-fit configuration the bushing expansion at room temperature produces an interference with the lug, and tensile hoop residual stresses that improve the fatigue life because the fatigue cycle range is reduced. The fretting is also reduced.

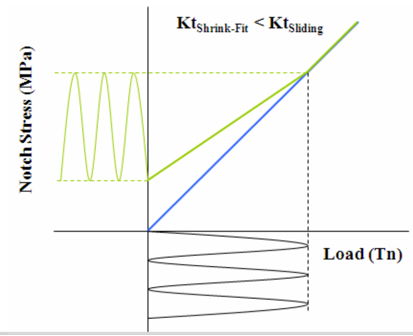
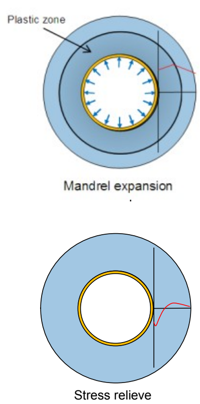


Fig. 15 - Local stress in shrink-fit

In the particular case of the cold-expanded bushings, the compressive residual stress field created around the lug hole after the bushing installation has a significant effect on the fatigue behaviour. Thus, an evaluation is required of those residual stresses, as well as a procedure to take them into account in the analysis.



COLD-EXPANDED

In the cold-expanded configuration, the bushing expansion due to the mandrel produces plastic deformation in some areas of the lug. After the mandrel removal, the material tends to recover the initial state, creating a compressive hoop residual stresses. These residual stresses highly improve the fatigue life due to the combined effect of decreasing the cycle mean stress and reducing the cycle range.

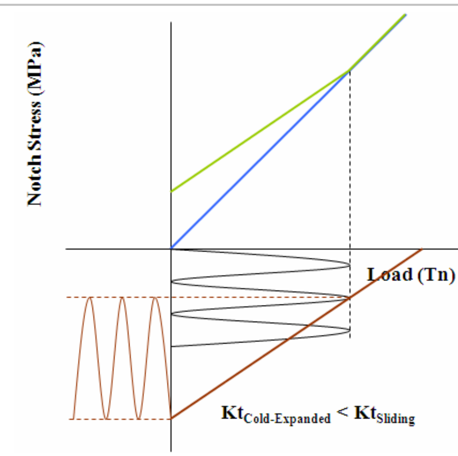


Fig. 16 - Local stress in cold-expansion

4.1 Load process simulations

The critical location is at the lug hole in a direction approximately perpendicular to the applied load. The stress concentration factor at this location is evaluated using the same FEM models developed for residual stress evaluation. The difference is that now the interaction between the outer radius of the pin and the inner radius of the bushing is introduced.

Once the initial stress state is determined (no stress for clearance-fit bushing, tensile hoop stress for shrink-fit bushing, compressive hoop stress for cold-expanded bushing), an axial load is applied to the pin.

In the real assembly, the bushing thickness is taken in such a way that after the cold-expansion and subsequent relaxation, the bushing inner diameter will be smaller than the pin's outer one. Then a reaming in the bushing is performed in order to get a clearance-fit with the pin.

In the FEM model this bushing reaming will not be simulated and, instead, initially the pin outer diameter is taken equal to the bushing inner diameter. The FEM solution is different depending on the bushing configuration.

- In the clearance-fit configuration there is no residual stress, and the load is applied to the pin shear surface.
- In the shrink-fit configuration there is a tensile residual stress in the lug after the bushing installation. After that, the load is applied to the pin shear surface.
- In the cold-expanded configuration, after the bushing cold-expansion and subsequent relaxation, the bushing inner diameter will become bigger than the pin's outer one. So just before the load application to the pin, there is a gap between the pin and the bushing. Then it an intermediate load step is introduced, with a very small load, in order to put the pin in contact with the bushing. To avoid instabilities, the interaction in this step includes the Abaqus property of stabilization, which simulates a viscous material between the pin and the bushing, with a decreasing rigidity as an incremental load is applied. In the last incremental load frame, the rigidity of the viscous material will be null, and the pin will be in contact with the bushing. After this intermediate stabilization step, the load is applied to the pin shear surface.

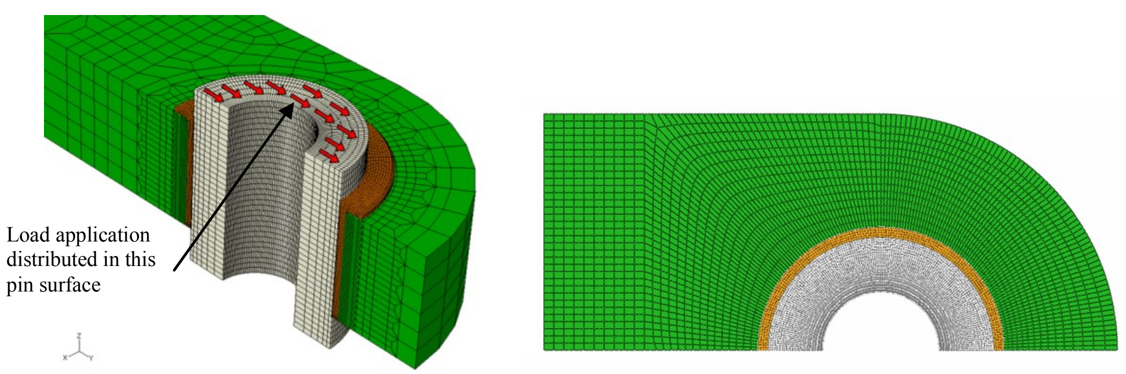


Fig. 17 - Pin load application

4.2 Stress-life approach

In this approach, the load spectrum applied to the lug (tons) is converted to notch stresses at the critical location using the graphs presented above. The initial residual stresses for shrink-fit and cold-expanded bushings have previously been evaluated using FEM models. The slope of the curves takes into account the Kt, also obtained from the FEM.

Then the local stress spectrum is processed by an in-house software that uses S-N curves data obtained for various R ratios (ratio between minimum and maximum cycle stresses), accumulating the damage with the Miner's rule.

4.3 Strain-life approach

In a similar way to the stress-life approach local stresses are calculated using the graphs shown at the beginning of section 4, but only for clearance-fit and shrink-fit bushing configurations.

For cold-expanded bushings, the cold-expansion process is simulated by an initial application of an overload, which produces a hoop residual stress equal to the one that has been calculated with the FEM models.

This initial overload and the subsequent spectrum are processed by in-house software, which applies Neuber's rule for notch stress evaluation and damage accumulation with Miner's rule. The material properties (cycle stress-strain curve and ε-N curves) are taken from Ref. 1.

4.4 Results

The real fitting is classified as a safe-life structure, so the interest is focused on the crack initiation life. Several fractographic analyses indicate that the initiation life is around two thirds of the total life.

The life improvement factor (LIF) of the cold-expanded bushings over the clearance-fit or shrink-fit ones is obviously dependent on the load level. More refined analyses that take into account variations of the measured test bending ratio (due to load eccentricity) in each of the specimens, produce a LIF of approximately 5.

The results obtained from the fatigue calculations are compared with tests in the following chart, for those cases when both clearance-fit and cold-expanded configurations are available. Plot test points at 54 Tn cold-expanded configuration have been corrected due to the fact that part of the test was carried out at a higher load.

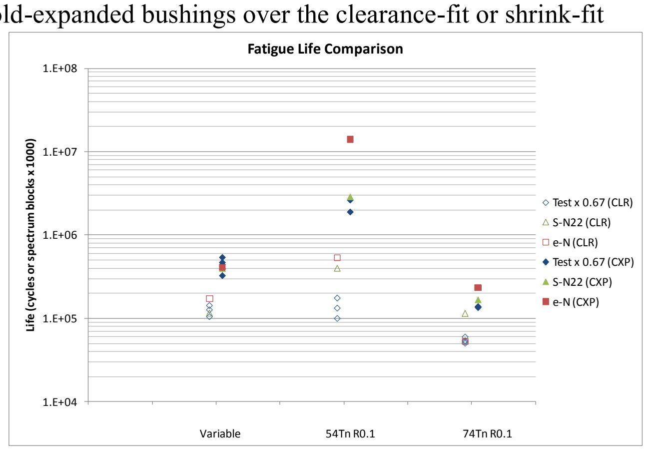


Fig. 18 - Fatigue life prediction vs test

In can be seen that, globally, stress-life approach gives better results than strain-life approach when comparing with tests. The variable amplitude test is better correlated than the constant amplitude ones. A higher difference is found in the clearance-fit (sliding) bushing configuration, which is attributed to possible fretting that is not considered in the fatigue estimation. The fretting would have much less effect on cold-expanded bushing, due to the high interference between the bushing and the lug.

5. Conclusion

Fatigue test results of a big aluminium lug (105 mm inner diameter) with three bushings configurations (clearance-fit, cryogenic shrink-fit and Force-Mate) under variable and constant spectrum loading have been presented. These results show a clear fatigue benefit of the cold-expanded bushing configuration. The LIF is around 5 for the variable spectrum, representative of the actual usage of the part.

A study on cold-expansion process finite element modellization has been made. Different FE models have been defined evaluating different characteristics as plastic strain representation, contacts simulation and material characterization.

Residual stresses in the lug after the cold-expansion process have been evaluated by means of FEM models using Abaqus/Std software. Both 2D and 3D models have been developed, which indicate that 2D FEM can be used as a preliminary estimate. A limited number of residual stress measurements using the hole-drilling method indicate reasonable match with 2D FEM predictions.

Fatigue life crack initiation evaluations using AIM analysis procedures have also been presented. For this particular application, stress-life approach gives a better correlation with test results than strain-life approach, considering all the specimens.

The predictions for clearance-fit configuration are un-conservative, probably due to fretting effects that have not been taken into account in the analysis.

The stress-life predictions for cold-expanded bushing (in which fretting effects should be less important due to the high interference) are reasonable, and could be used for a preliminary assessment of the fatigue behaviour of cold-expanded bushing. Based on this study, AIM is preparing a predictive method to assess the fatigue analysis of this kind of elements.

Further work could be required for better definition of crack initiation in test specimens, and residual stress measurements and correlations with test specimens.

6. Acknowledgments

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7. References

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