Residual stress effect on fatigue life of a cold worked rivet hole

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Abstract. The use of riveting as assembly technique, especially in the aeronautical construction, requires the implementation of several holes in aluminium alloy sheets, which leads to an inhomogeneous stress and strain fields distribution and to a stress localization in the drilled zones which will be affect the fatigue life of 2024-T3 aluminium alloy.

The cold expansion is largely employed to obtain improvement in fatigue life of rivet holes. This paper presents the results of an experimental work whose main objective was to evaluate the effects of the residual stress field caused by the cold expansion of the hole on improving the fatigue life and on the crack initiation and propagation in the 2024-T3 aluminium alloy. X- ray diffraction is used to measure the residual stresses resulting of the cold expansion on the hole edge.

1. Introduction

The assembly stresses of various parts composing a structure produce significant concentrations within material. Indeed, although welding is today introduced in the aeronautical structure, the riveting assembly present more 95% more of junctions among which the totality of critical parts. The rivet holes produce a stress concentrated regions where cracks can form and grow, often hidden beneath another layer of aluminium or by the head of the rivet. The industrial analyses led previously on these problems show that improvements are possible in the first millimetres of the crack life **[1]**. Indeed, if today the propagation of relatively long cracks is well controlled, the situation is quite different for low size cracks subjected to a local request complex as it is the case within an assembly.

The aeronautical structures components are generally assemblies by rivet which lead to geometrical discontinuities and to a stress concentration zones; the risks of initiation and propagation of the fatigue cracks are located close to these zones. It is often advantageous to drill a small diameter hole, called a pilot hole, in the rivet hole location prior to drilling the final diameter rivet hole. This pilot hole then becomes a guide for the larger diameter bit. Drilling two holes obviously requires more time, which can become a large cost concern when thousands of holes are drilled. The main objective of this work is to evaluate the effect of the cold expansion of rivet holes on the fatigue behaviour and on improving the fatigue life.

2. Specimens geometry

The specimen geometry and dimension are shown in figure 1 It is the central hole (Ø6) which is the subject of the study

3. Specimens preparation

Specimens, 50 mm wide and 5 mm thick, were obtained by a plate of dimension 1250x2500 mm (AIR9048 ASNA3010) of aluminium alloy 2024-T3. They were shaped in order to the load be applied along the lamination direction, two batches of eight specimens each one are prepared, batch

1 represent specimens which hole is drilled by an ordinary bit (6 mm directly), in the second batch we drill a small diameter hole (3 mm), called a pilot hole, prior to drilling the final diameter of 6 mm by a reamer.

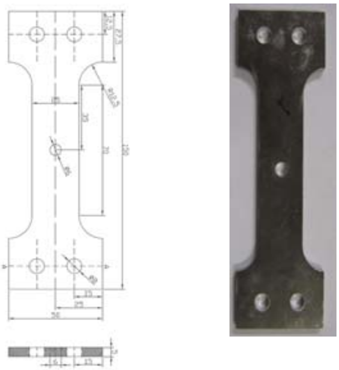


Figure 1 **:** Specimens geometry and dimension (dimension in mm).

4. Material characteristic

The material used for this study was aluminium alloy AERO TL 2024-T3 used especially for the aeronautical engineering. Mechanical properties of alloy are reported in table 1.

Ultimate strength	476	Mpa
Yield strength	378	Mpa
Displacement	18.1	%
Elastic modulus	72.22	Gpa
Poisson's ratio	0.33	

Table 1: Mechanical properties of 2024-T3 aluminium alloy.

5. Stress-strain behaviour of the material

The stress-strain behaviour of the material was obtained from simple tensile tests and is shown in figure 2.

6. Observation of the drilled holes by (SEM)

The central hole of 6 mm of diameter (Fig. 1) is drilled by using a pilot hole of 3 mm of diameter and then followed by a reamer that would bring the hole size to the desired diameter.
The scanning electron microscopy showed that the entrance diameters of the holes are higher than the exit diameters which indicate that the drilled holes are conical and not cylindrical (Fig.3).

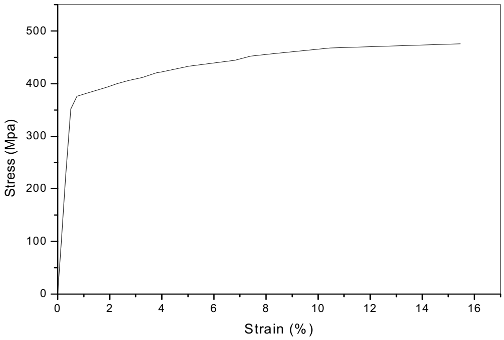


Figure 2: Stress-strain diagram for Al-alloy 2024-T3.

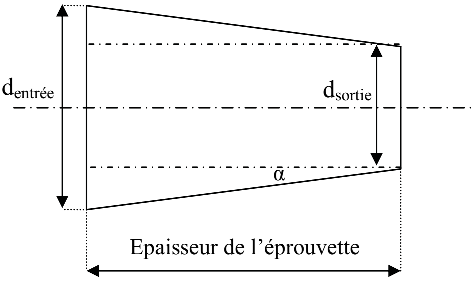


Figure 3 : Hole conicity

Holes conicity can be calculated by the following equation

$$\mathrm{tg}\,\alpha = \frac{\left(d_{entrance} - d_{exit}\right)/2}{Thickness} \tag{1}$$

The average value of the angle α for the first batch specimens (drilled) is 1.334° and for the second batch is 0.412°

7. The cold expansion process

To achieve cold expansion a tapered pin was forced through the hole locally yielding the material to create a plastic region (Fig.4***)***. When the surrounding material, which is elastically deformed, springs back from the expanded state the yielded material contracts resulting in compressive tangential residual stress around hole [2, 3], this residual stress will be measured using X-ray diffraction. In addition, the rubbing of the tapered pin on hole can smooth the surface which and this may have a positive effect on fatigue life improvement. The pin was pushed through the hole using a 10 KN Instron fatigue machine.

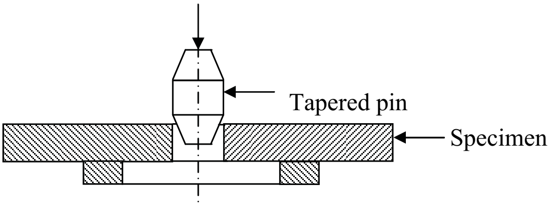


Figure 4 : Cold expansion of hole using tapered pin

7.1. Dimension of the tapered pin

In the aerospace industry diametrical interferences between 2 and 6% are used for cold expansion [4, 5 and 6] but because little information is available about residual stress distributions it is difficult to choose which interference is an optimum for improving fatigue life. Diametrical interference between hole and the cylindrical part of the tapered pin is 0.3 mm (5% of hole diameter), this choice is due to the hole conicity. Figure 5 showed the dimensions of the tapered pin.

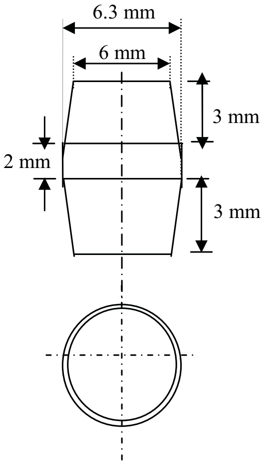


Figure 5: Tapered pin used for the cold expansion.

8. Measurement of the residual stress caused by the tapered pin using X-ray diffraction

The X-ray diffraction measurements were performed on a 4-circle goniometer, the residual stress measurement was made on 8 points in the two radial and circumferential directions (σ_r and σ_θ) around the hole (fig.6) and on both faces of the specimen, entrance and exit faces.

Each measured point corresponds to the centre of one irradiated rectangle area of 2 X 1 mm ^{2} (1mm in the radial direction). The aluminium (422) reflection was used at a diffraction angle of $2\theta = 137.44°$. This means a mean depth penetration of 30 µm for the X-ray radiation.The residual stress results are presented in Figure 7 for both entrance and exit faces. A polynomial fitting of the values is also suggested in the figure. Compressive stresses are observed in the vicinity of the hole, with values higher on the exit face than in the entrance face, confirming the through-thickness variation of the stress field.

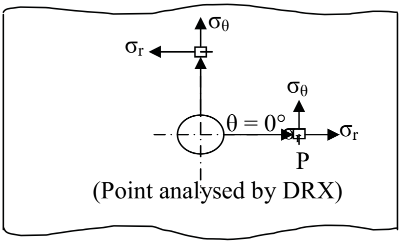
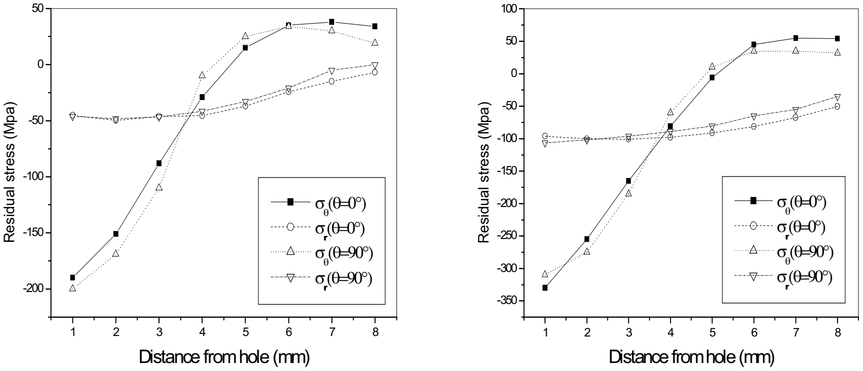


Figure 6: Radial (σ_r) and circumferential (σ_θ) stresses for θ = 0° and θ = 90°.



Entrance face

Exit face

Figure 7 : Residual stresses introduced by the tapered pin.

9. Fatigue test

Fatigue tests were carried out using constant amplitude, sinusoidal cycling loads with a load ratio R of 0.1. The fatigue tests were run at a frequency of 20 Hz in a servo hydraulic Instron machine. The fatigue tests parameters must be selected in such way that the maximum stress level for all tests was 96 Mpa (29.26 % of the yield stress) which corresponds to a load of 12 kN. With k_T of 3.02 the stress adjacent to the hole was below the yield stress of the material. This was considered essential because yielding the material adjacent to the hole would possibly negate any residual stresses placed in the material by the cold expansion process.

Eight fatigue tests will be made for each specimen batch (with and without cold expansion). All fatigue lives reported on figure 8 correspond to specimen failure. The cracks which preceded the failure were firstly initiated on the entrance faces where the values of the residual stresses are weaker compared to the exit faces.

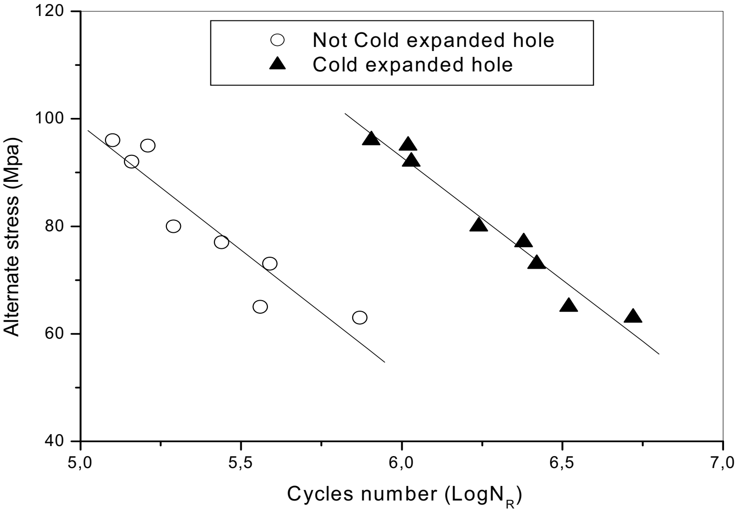


Figure 8: Wöhler curves for the two batches of specimens.

9.1 Fatigue life comparison

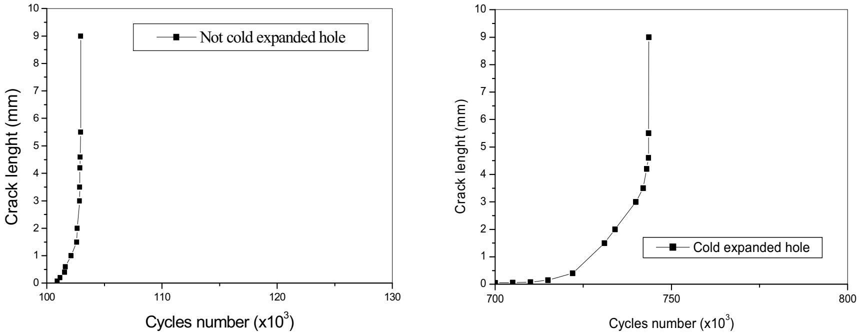
Figure 8 present the Wöhler curves of the two specimen's batches.
On this figure we can distinguish three fields:

- A first fatigue zone under strong constraint, where the failure intervenes after a low cycles number (points which corresponds to the low values of the cycles number)
- A second zone, where the failure is reached after a more significant cycles number, this number grows when the constraint decrease (points in the mediums).
- A third zone, under low constraint for which the failure does not occur before a given cycles number (last points which corresponds to the low values of constraints).

As the fatigue results show the cold expanded specimens generally achieved a fatigue life improvement of almost 7 times compared to the 'as drilled' specimens. The increase in fatigue life at low alternating stresses is greater than at high alternating stresses and one cold expanded specimen did not break at the lowest alternating stress considered even nearly nine million cycles. These results showed the beneficial effect of the compressive residual stresses caused by the cold expansion on improving the fatigue life.

9.2 Cracks growth comparison

During the fatigue tests many images were acquired in order to locate the crack initiation and propagation. A camera with 4x zoom and a resolution of 4 million of pixels, interfaced with a computer, was used. As the curves of figure 9.a and 9.b show the crack initiation in the cold expanded specimens make a delay of 6 to 7 times compared to the 'as drilled' specimens. In addition the crack growth is very slow for the cold expanded specimens.



-a- -b-

Figure 9: Comparison of the crack propagation: a) Cold expanded hole, b) not cold expanded hole

The recorded delay in the crack birth and growth show the beneficial effect of the residual stresses caused by the cold expansion.

10. Conclusions

This work treated the effect of the compression residual stresses around the hole on the fatigue behaviour of material.

The fatigue tests showed the beneficial effect of the cold expansion on improving fatigue life.

In addition, the crack birth and growth comparison show the delay recorded in the starting and the cracks growth.

The following deductions were obtained:

- A drilled hole is conical, it is not cylindrical, the entrance diameter is higher than the exit diameter.
- The residual stresses are not constant; they vary through the specimen thickness.
- Compressive stresses are observed in the vicinity of the hole, with values higher on the exit face than in the entrance face, confirming the through-thickness variation of the stress field.
- The fact of imposing a compressive stress field around the hole gives improving in fatigue life of almost 7 times.
- A delay of 6 to 7 times was observed in the cracks initiation of the cold expanded specimens.
- During fatigue tests the first cracks were initially observed on the entrance faces where the residual stresses values are less low compared to the exit faces.

References

[1] B. Journet, F. Congour deau, prévision de la fissuration par fatigue des alésages de jonctions rivetés, In : Colloque National MECAMAT, Aussois, 2003.

[2] Chandawannich N, Sharpe Jr WN. An experimental study of fatigue crack initiation and growth from cold worked holes. Engineering Fracture Mechanics 1979; 1(1):609-20.

[3] Link RE, Sanford RJ. Residual strains surrounding split-sleeve cold expanded holes in 7075-T651 Aluminium. J Aircraft 1990; 27(7):599-604.

[4] Ozdemir AT, Edwards L. Measurement of the three-dimensional residual stress distribution around split –sleeve cold-expanded holes. Journal of Strain Analysis 1996;31(6);413-21.

[5] Ozdemir AT, Hermann R. Effect of expansion technique and plate thickness on near-hole residual stresses and fatigue life of cold expanded holes. Journal of Material Science 1999; 34; 1243-52.

[6] Hermann R. Three-dimensional stress distribution around cold expanded holes in aluminium alloys. Engineering Fracture Mechanics 1994; 48(6); 819-35. growth behavior at fastener holes. Materials science and Engineering A225 (1997) 196-203.