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THE EFFECT OF COLD EXPANSION ON THE FATIGUE BEHAVIOUR OF 2024-T3 ALUMINIUM ALLOY

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Résumé

L'utilisation du rivetage comme technique d'assemblage surtout dans la construction aéronautique, nécessite la mise en oeuvre de plusieurs trous dans les tôles d'alliage d'aluminium, ce qui mène à une distribution inhomogène des champs de contraintes et de déformations et à une localisation de surcontraintes dans les zones percées ce qui influe sur la durée de vie de l'alliage en fatigue.

Cet article présente le résultat d'un travail expérimental dont le but principal est d'évaluer l'effet de la présence des contraintes résiduelles de compression imposées par le processus de l'expansion à froid du trou à l'aide d'une goupille conique sur l'amélioration de la durée de vie en fatigue et sur le retard de l'initiation et de propagation des fissures.

Une analyse des contraintes résiduelles sera faite sur les deux faces de l'échantillon en utilisant la technique de la diffraction des rayons X.

Mots clés **:** *Trou de rivet, expansion à froid, contraintes résiduelles, durée de vie*

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 affect the fatigue life of 2024-T3 aluminium alloy.

Cold expansion is largely employed to obtain improvement in fatigue life of rivet holes. This paper presents the results of 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 2024-T3 aluminium alloy. X-ray diffraction is used to measure the residual stresses resulting from the cold expansion on the hole edge on both specimen faces.

Keys words **:** *Rivet hole, cold expansion, residual stresses, fatigue life*

M. ELAJRAMI[1]
M. BENGUEDIAB[1]
G. RONALD[2]

[1] Laboratory of Material and Reactive Systems - Department of Mechanical Engineering University of Sidi bel Abbes, Algeria

[2] Research Center and Transfer of Technology – GeM (EMM) University of Nantes - France

ملخص

إن استعمال تقنية البرشمة للتثبيت خاصة في صناعة الطيران يتطلب وجود عدة ثقوب في صفائح خليط الألمنيوم مما يؤدي إلى توزيع غير متجانس للاجهادات والتشوهات وتمركزها بشدة حول المناطق المثقوبة الشئ الذي يؤثر سلبا على عمرالخليط تحت تأثير الإجهاد.

هدا المقال يمثل نتائج عمل تجريبي يهدف أساسا إلى تقييم تأثيروجود حقل اجتهادات كامنة وضاغطة متولدة عن طريق توسيع قطر الثقب على البارد باستعمال خابور مخروطي على عمر الخليط المجهد وعلى تأخرظهور وانتشارالخدوش. قياس الاجهادات الكامنة يتم بواسطة تقنية انكسار الأشعة (س).

الكلمات المفتاحية: *الثقب- التوسع على البارد- الاجهادات الكامنة- مدة الحياة*

The assembly stresses of various parts composing a structure produce significant concentrations within the material. Indeed, although welding is today introduced in the aeronautical structure, the riveting assembly present more than 95% of junctions among critical parts. The rivet holes produce stress concentrated regions where cracks can form and grow, often hidden beneath another layer of aluminium or by the head of the rivet. Previous industrial analyses of 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 small cracks subjected to a local complex request as is the case within an assembly.

Aeronautical structural components are generally assembled by riveting which leads to geometrical discontinuities and to stress concentration zones; the risks of initiation and propagation of the fatigue cracks are high 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.

SPECIMEN GEOMETRY

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

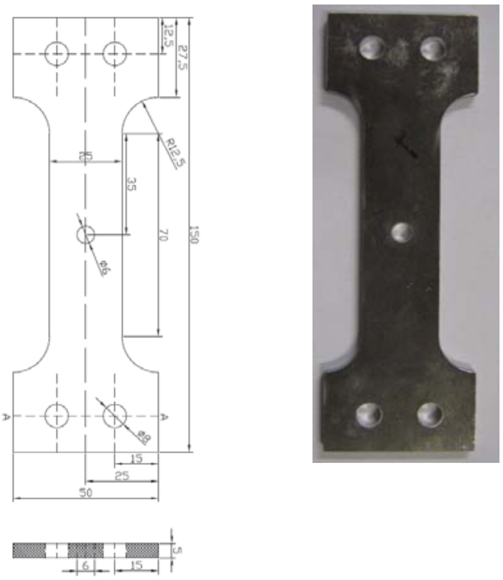


Figure 1 : Specimen geometry and dimensions (mm)

SPECIMEN PREPARATION

Specimens, 50 mm wide and 5 mm thick, were obtained from a plate of dimension 1250x2500 mm (AIR9048 ASNA3010) of aluminium alloy 2024-T3. They were shaped so that the load would be applied along the lamination direction. Two batches of eight specimens each were prepared: in batch 1 the hole was drilled directly using an ordinary bit (6 mm); in batch 2 a small hole (3 mm), called a pilot hole, was drilled prior to reaming to the final diameter (6 mm).

MATERIAL CHARACTERISTICS

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

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.

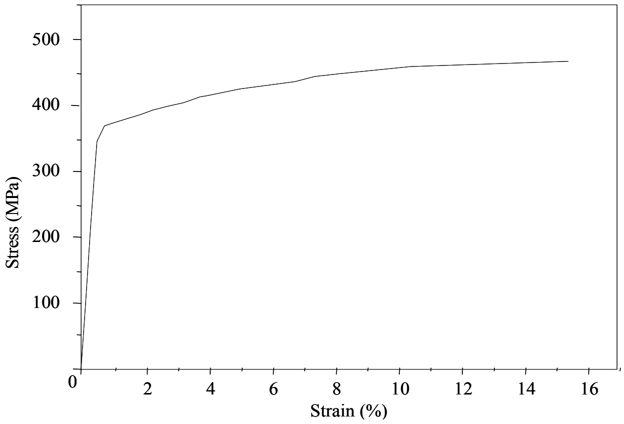


Figure 2 : Stress-strain diagram for Al-alloy 2024-T3.

OBSERVATION OF THE DRILLED HOLES BY SEM

Scanning electron microscopy showed that the entrance diameters of the holes are larger than the exit diameters which indicate that the drilled holes are conical and not cylindrical (figure 3).

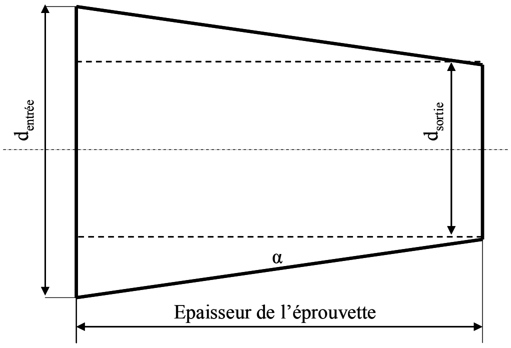


Figure 3 : Hole conicity

The hole conicity can be calculated using the following equation :

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

The average value of the angle α for batch 1 (drilled directly) is 1.334. For batch 2 it is 0.412°.

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 (figure 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.

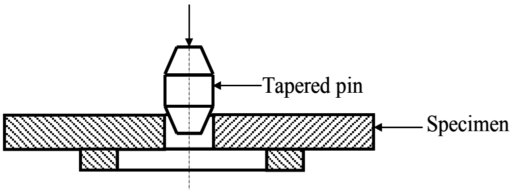


Figure 4 : Cold expansion of hole using tapered pin

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]. However, because little information is available about residual stress distributions, it is difficult to choose which interference is an optimum for improving fatigue life. Diametral interference between the hole and the tapered pin of the cylindrical part is 0,3 mm (5% of the hole diameter), this choice is due to the hole conicity. Figure 5 shows the dimensions of the tapered pin.

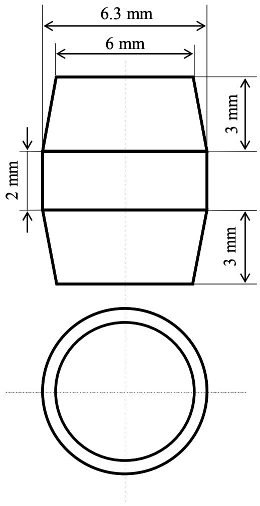


Figure 5 : Tapered pin used for the cold expansion

MEASUREMENT OF THE RESIDUAL STRESS CAUSED BY THE TAPERED PIN USING X-RAY DIFFRACTION

X-ray diffraction measurements were performed on a 4-circle goniometer. The residual stress measurement was made at 8 points in the two radial and circumferential directions (σ_r and σ_θ) around the hole (figure 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 mm ^{2} (1 mm in the radial direction). The aluminium (422) reflection was used at a diffraction angle of 2θ = 137.44°, giving 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.

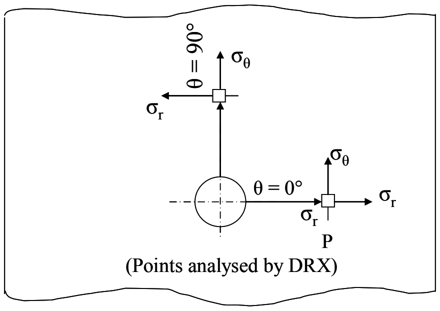


Figure 6 : Radial (σ_r) and circumferential (σ_θ) stresses for θ = 0° and θ = 90°.

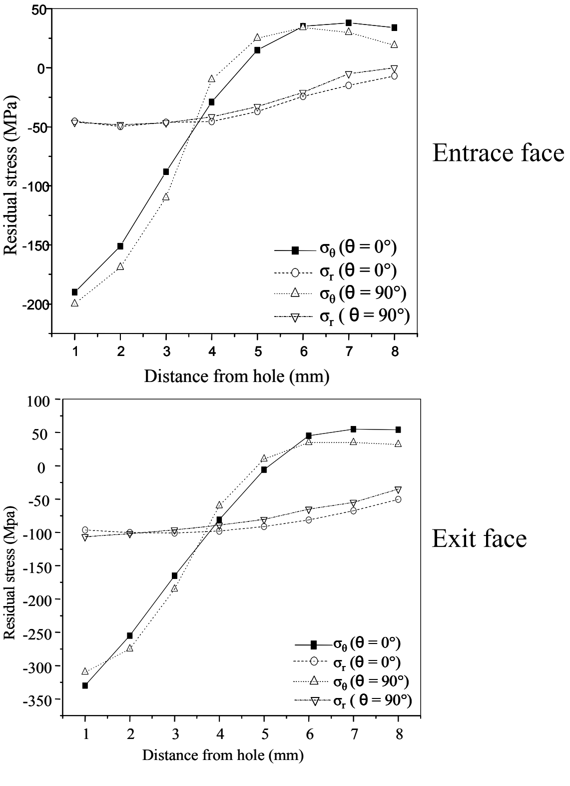


Figure 7 : Residual stresses introduced by the tapered pin

FATIGUE TESTS

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 test 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 were made for each condition (with and without cold expansion) and each batch. All fatigue lives reported in Fig. 8 correspond to specimen failure. The cracks which preceded the failure initiated on the entrance faces where the residual stresses are weaker compared to the exit faces.

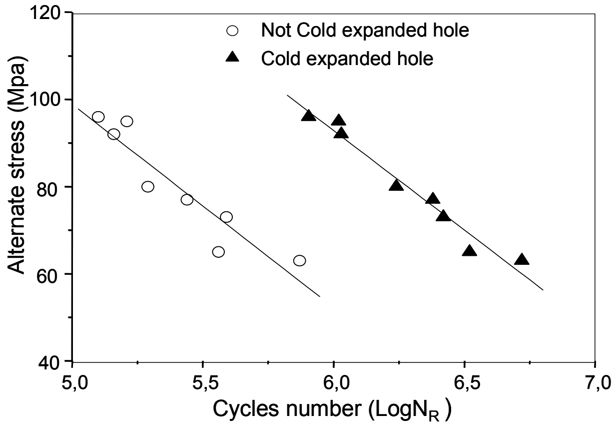


Figure 8 : Wöhler curves for the two batches of specimens.

1. Fatigue life comparison

Figure 8 presents the Wöhler curves of the two specimen's batches.

On this figure we can distinguish three fields:

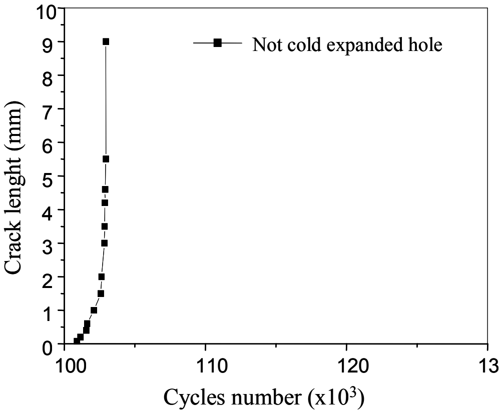
- A first fatigue zone under strong constraint, where the failure intervenes after a low cycle number
- A second zone, where the failure is reached after a larger cycle number. This number grows when the constraint decrease (points in the mediums).
- A third zone, under low constraint for which the failure does not occur before a given cycle 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.

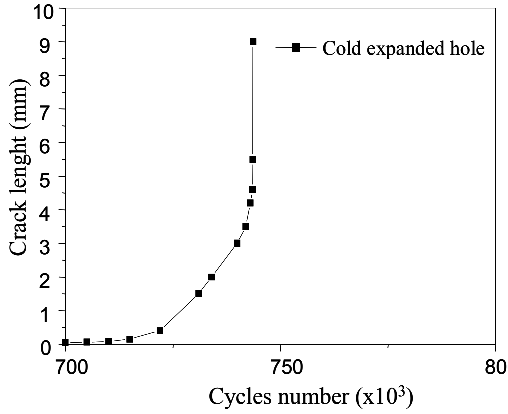
These results showed the beneficial effect of the compressive residual stresses caused by the cold expansion on improving the fatigue life.

2. Crack 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 pixels, interfaced with a computer, was used. As the curves of figures 9.a and 9.b show, crack initiation in the cold expanded specimens is delayed by 6 to 7 times compared to the 'as drilled' specimens. In addition the crack growth is very slow for the cold expanded specimens.



(a) Cold expanded hole



(b) Not cold expanded hole

Figure 9 : Comparison of the crack propagation

The recorded retardation of crack initiation and propagation show the beneficial effect of the residual stresses caused by the cold expansion.

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; crack initiation and propagation were delayed following cold expansion.

The following deductions were made:

- A drilled hole is conical, not cylindrical; the entrance diameter is larger 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, indicating a through-thickness variation of the stress field.
- Imposing a compressive stress field around the hole improves the fatigue life by almost 7 times.
- A delay of 6 to 7 times was observed in the crack initiation in the cold expanded specimens.
- During fatigue tests cracks initiated on the entrance faces where the residual stress values are smaller (less compressive) compared to the exit faces.

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