Effect of various drilling procedures on the fatigue life of rivet holes

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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 field's distribution and to stress localization in the drilled zones which will be affecting the fatigue life of 2024-T3 aluminium alloy. In addition the machining process used for drilling can increase or decrease the fatigue life of materials. This paper presents the results of an experimental study whose main objective was to determine which drilling procedure least affect the fatigue life and to show the role of the residual stresses introduced by each process on the fatigue behaviour of material. For that four drilling procedures are compared in fatigue: Direct drilling bit of the wanted diameter, drilling a small diameter hole called a pilot hole in the rivet hole location prior to drilling the final diameter using a reamer, water jet and finally punching. Hole's quality is compared in two parameters: Conicity and surface quality which will be observed using a scanning electron microscopy (SEM). X-ray diffraction is used to determine the residual stress profile resulting of each drilling procedures.

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 fatigue life of rivet holes is affected by the machining process used **[2]**, although drilling may appear to be a simple process perhaps due to the fact that is so common, it is in fact deceptively complex. The drill bit has a geometrically complex helical shape and is relatively flexible along its axis **[3]**. A sharp, new bit should quickly and easily cut through the workpiece with little plastic deformation **[4]**. An old bit would likely expand the hole bore plastically, resulting in larger residual compressive hoop stresses when the stresses relax **[4]**, which would retard crack growth **[5]**.

The objective of this study is to compare the fatigue life of four drilling hole procedures and to show the role of the residual compressive stresses introduced by each drilling process and to evaluate the effect of the cold expansion of rivet holes on the fatigue behaviour and on improving the fatigue life of 2024 –T3 aluminium alloy.

2. Specimens and material characteristics

2.1 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

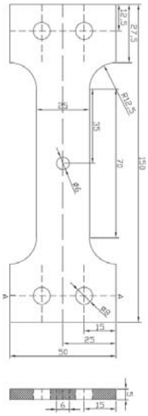


Fig. 1: Specimens geometry and dimension (dimension in mm).

2.2 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, five 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, in the third batch the hole is drilled by water jet and in the fourth it is drilled by punching, batch five is reserved for the cold expansion process and holes were drilled using a pilot hole.

2.3 Material characteristics

The material used for this study was aluminium alloy AERO TL 2024-T3 used especially for the aeronautical engineering **[6]**. Mechanical properties of alloy are reported in table 1

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

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

3. Observation of the drilled holes by (SEM)

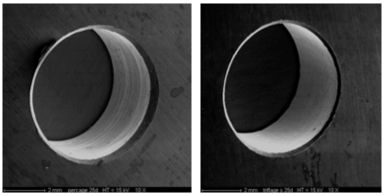
To have an idea on the interior surface quality of holes, we have proceeded to an observation by S.E.M (Scanning Electron Microscopy). This observation showed that the hole is not cylindrical, it is conical, its entry face diameter is higher than the exit face diameter, for that we will compare the holes conicity carried out by the various drilling processes. The average values of the angle α was calculated for the various drilling processes and reported in table 2. The comparison of the conicity shows that the most conical holes corresponds to the drilling process per punching and the least conical, almost cylindrical, corresponds to the drilling process which we have used a pilot hole, what confirms that the pilot hole becomes a guide for the second drilling larger diameter .
The conicity of the holes drilled by water jet comes in third position after that of those drilled directly by bit and before that of those drilled by punching.
In general the hole conicity is due to the diameter difference between the entrance and the exit faces.

Drilling Process	Conicity (angle °)
Bit (directly Ø6)	1.334 °
Pilot hole	0.412 °
Water jet	2.98 °
Punching	3.11 °

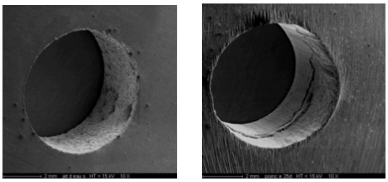
Table 2: Holes conicity for various drilling process.

3.1 Holes surface quality

The images of figure 2, obtained by the scanning electron microscopy, show a comparison of surface qualities of various drilling processes for an enlargement of 10 times.



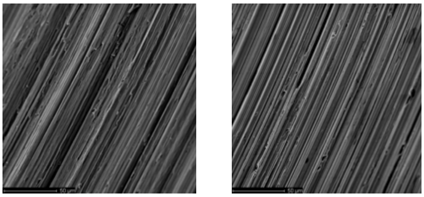
Drill bit Pilote hole



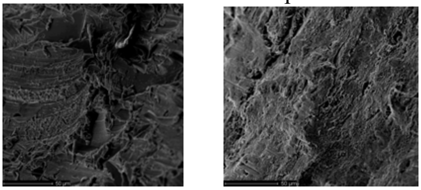
Water Jet Punching

Fig. 2: Comparison of surface qualities of various drilling processes (10X).

These images show that the drilling process using a pilot hole gives a clean surface quality, smooth and less outstanding. The bad surface quality given by punching and water jet drilling processes was very clearly. Another comparison of the images showed in figure 3, obtained with an enlargement of 500 times, always shows the surface cleanliness obtained by the pilot hole drilling process.



Drill bit pilote hole



water Jet Punching

Fig. 3: Comparison of surface qualities of various drilling processes (500X).

To conclude, this comparison showed that to have a straighter hole is advantageous to drill a small hole prior to drilling the final diameter, this pilot hole 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 use of a pilot hole may also affect hole quality, since the primary drill bit has less material to remove. This makes for faster, straighter drilling and less wear on the bit. Less heat is generated with the final bit, and the pilot hole may allow for better cooling and chip removal.

4. Residual stress measurement by DRX

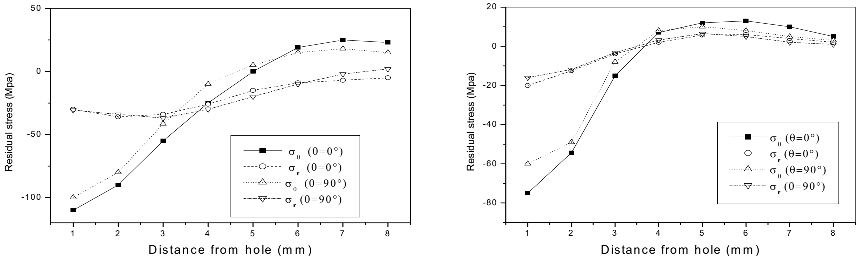
Plastic deformations around the hole vary according the drilling process used, which gives a different residual stresses fields. The X-ray diffraction measurements were performed on a 4-circle goniometer, the residual stress measurement was made on 8 points in the two radial and circumferential directions (σ_r and σ_θ) around the hole 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 **[7]**.

4.1 Specimen without hole

In order to check if the 2024-T3 alloy is constrained or not, X-ray diffraction measurement was carried out on specimen without hole, the results shows that for the plan (422), the radial and the circumferential residual stresses are respectively about -19 Mpa and - 28 Mpa which are low values and consequently the material is not constrained. It is completely logical because the sheet was obtained by rolling then it was subjected to a heat treatment T 351 which makes relaxing the residual stresses.

4.2 Drill bit

Figure 4 shows the residual stresses corresponding to this drilling process and measured by X-rays diffraction on the entry and exit faces.



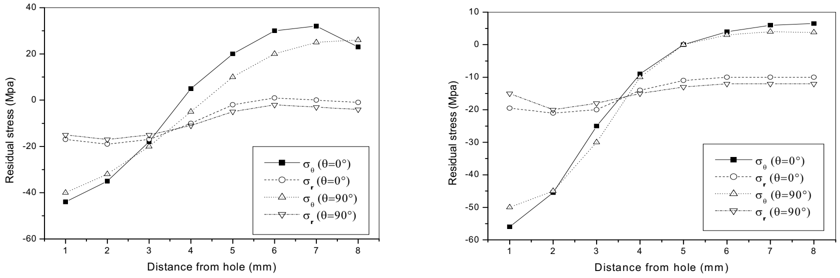
-a- **-b-**

Fig.4: Residual stresses for θ = 0° and θ = 90°; - a- entrance face, -b- exit face.

A simple analysis of this figure makes it possible to note that the residual stresses in the exit face are higher than those measured in the entrance face, then the residual stresses are not constant, they vary through the specimen thickness. Since the hole is not cylindrical, it is conical where the entrance diameter is higher than the exit diameter, we will have consequently in the exit face a higher contact bit-matter what explains why the stress values are higher than those measured in the entrance face.

In addition, the drill bit process introduced a compressive stresses on a radius of 3 mm around the hole edge of 6 mm in diameter. While moving away from the edge hole, the residual stress gradient joined that of the initial state of material.

4.3 Pilot hole



-a- **-b-**

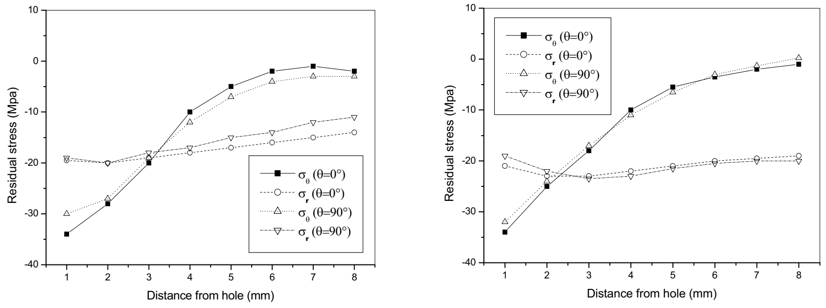
Fig.5: Residual stresses for θ = 0° and θ = 90°; - a- entrance face, -b- exit face.

The results obtained for this case, as figure 5 shows, indicate that the residual stresses resulting from thisdrilling process on the entrance and the exit faces are much weaker compared to those of the drill bit process, that is explained by made that the residual stresses layer introduced by the drilling of a hole of 3 mm in diameter (pilot hole) was removed while drilling the final diameter of

6 mm using a reamer. Thus the reamer presents less effort and less plastic deformations which gives low residual stresses values around the hole.

4.4 Water jet

Figure 6 shows the residual stresses obtained for this case.



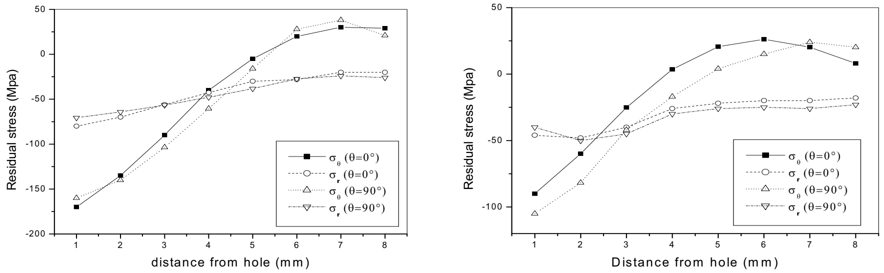
-a- -b-

Fig.6: Residual stresses for θ = 0° and θ = 90°; - a- entrance face, -b- exit face.

For this case, it noticed that the radial and circumferential stresses on the entrance and the exit faces are almost the same for θ = 0° and θ = 90° and the stress values converge to those measured for the without hole specimen's case. Thus water jet drilling did not change the initial state stress in the specimen. Its advantage is that the hole contour does not subjected to a local heating and consequently few of residual stresses and deformations.

4.5 Punching

According to figure 7, the residual stresses resulting from punching have the greatest values compared to the other drilling processes, which means that this process imposes great plastic deformations on material and consequently a residual stress field more significant.



-a- -b-

Fig.7: Residual stresses for θ = 0° and θ = 90°; - a- entrance face, -b- exit face.

5. 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 hole fabrication procedure. Eight fatigue tests will be made for each drilling process. 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.

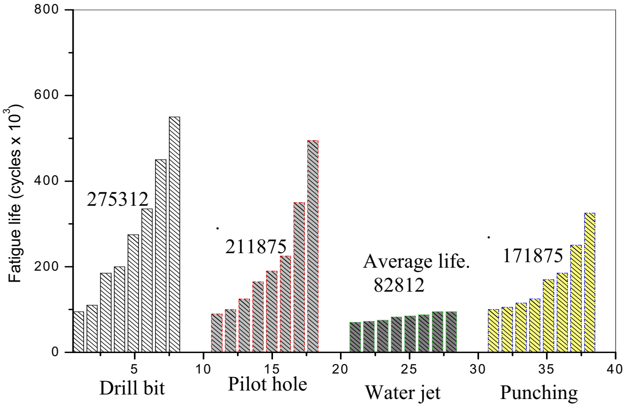


Fig. 8: Effect of drilling procedure on fatigue life.

Figure 8 shows that the weaker average fatigue life corresponds to the specimens which holes are fabricated by water jet, this drilling process does not affect the initial stress state in the material, consequently few residual stresses and deformations. The absence of the residual stresses and the bad surface quality were the cause of the short specimen's life. For the specimens which holes are carried out by punching, although this process imposes great plastic deformations and consequently more significant residual stresses, the average fatigue life remain less weak compared to the drill bit and pilot hole processes, that is due to the bad surface quality which leaves the punch (scratches, gouges, burs and irregularities in the surface). The comparison of the two drilling procedure which gives the bad surface quality(water jet and punching) shows that the process which introduces more residual stresses around the hole have a higher average fatigue life. The same remark is noted for the two drilling procedure which gives a good surface quality. From there, we deduce the beneficial effect of the residual stresses in the improvement of the fatigue life.

In terms of cut precision and surface quality, it is the drilling with a pilot hole which is most adequate. Thus the fatigue life fastener hole does not depend only on the residual stresses around the hole but also on the surface quality of the hole, because a badly made hole, with small irregularities can magnify the stress and increase the chances of crack initiation which will precipitate the material failure. So that, for the improvement of the fastener hole fatigue life, it is beneficial to have a compressive residual stresses around the hole accompanied by a good surface quality which will retarded the cracks initiation and propagation.

6. Conclusions

The objective of this paper was to evaluate the residual stresses introduced by various drilling procedure of the rivet hole in aluminium alloy Al2024-T3 and to compare them in fatigue.

The work presented in this study was devoted to the measurement of the residual stresses by the X-ray diffraction and to the fatigue tests.

Four fabrication procedures of the fastener hole were used. Observations by Scanning Electron Microscopy were carried out with the aim of comparing surface qualities and measuring the holes conicity resulting from each machining process.

Each fabrication procedure gives a different residual stress field around the hole, the fatigue tests shows a beneficial effect of the residual stresses on fatigue life improvement.

This study allowed deducing the following conclusions:

- A drilled hole is conical, it is not cylindrical and the entrance face diameter is also higher than the exit face one.
- The residual stresses are not constant, they vary through the specimen's thickness
- The residual stresses measured on the exit faces are higher than those measured on the entrance faces.
- This stresses are maximum on the hole edge, while moving away they take low values.
- The compressive residual stresses caused by a drilling process which give a good surface quality makes increase the fatigue life.
- For the all fatigue tests, the cracks were observed firstly on the entrance faces where the residual stresses values are less low compared to the exit faces.

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