Residual stress and reduction of the stress concentration factor in rivet holes of 2024 –T3 aluminium alloy

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Abstract. This paper presents a numerical study whose main objective was to analyze by the 2D finite element method the effects of the cold expansion on the variation of the stress field and the influence of the residual stress on the reduction of the stress concentration factor in rivet holes of 2024-T3 aluminium alloy sheet.
This analyze was done according the plate ligament and the hole edges using an uniaxial tensile load, the obtained results confirmed the phenomena of the retard of crack initiation and propagation experimentally observed.

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.
The objective of this paper is to analyze by the 2D finite element method the effects of the cold expansion on the variation of the stress field and the influence of the residual stress on the reduction of the stress concentration factor in rivet holes of 2024-T3 aluminium alloy sheet.

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. Material characteristic

The material used for this study was aluminium alloy AERO TL 2024-T3 used especially for the aeronautical engineering **[2]**. 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.

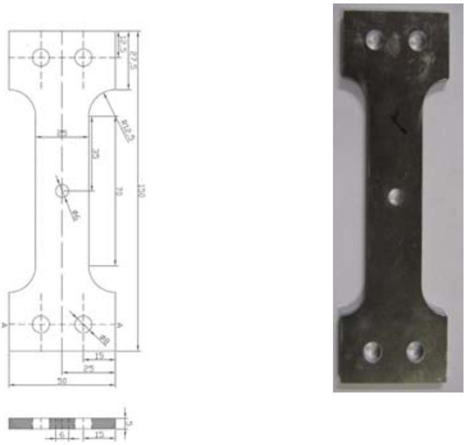

Figure 1 **:** Specimens geometry and dimension (dimension in mm).

4. Specimen meshing

Figure 2 shows the hole edges and the meshing of the specimen by finite elements using the FRANC2D software.

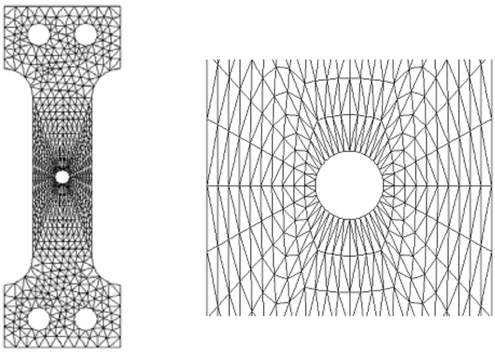

Figure 2: Specimen meshing and hole edges

5. Analyse

Firstly, to give an idea of the stress and the strain distribution around the hole, we studied those variations according the specimen ligament and according the hole edges. Uniaxial load of 28 KN without the effect of the residual stresses was choice.
Secondly, to illustrate the effect of the cold expansion of the hole on the variation of the stress and strain fields, the same analyse was done with the presence of the residual compressive stresses. In this case a variety of load was used (14 KN, 20 KN and 28KN).

5.1. Simulation of the cold expansion process

Experimentally the cold expansion is assured by the interference of diameter (tapered pin-hole), the results of this expansion is a plastic zone due to the compressive stress field imposed by the tapered pin. Numerically this field well be simulated by loading the edges nodes of the hole (Figure 3).

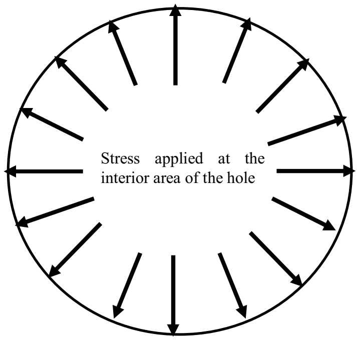

Figure 3: Simulation of the expansion process

This loading was choice in the way to can be plastically deformed the hole edges to give birth of compressive residual stresses.

5.2. Plastic zone resulting to the expansion

A punctual load of 400 Mpa was choice, this load give a circular plastic zone around the hole of ray equal to 3/10 of the length of the specimen ligament (Figure 4)

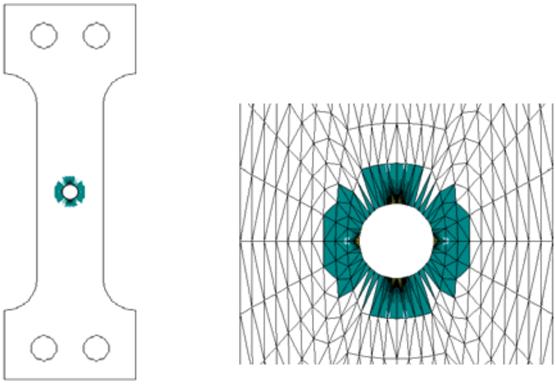

Figure 4: Plastic zone due to the simulated expansion

5.3. Variation of the compressive residual stresses numerically simulated according the specimen ligament

Figure 5 show the variation of the compressive residual stresses according the ligament of the specimen, from the edge of the hole to the edge of the specimen.

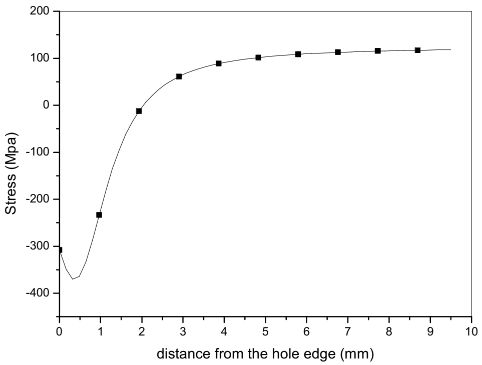

Figure 5: Residual compressive stresses variation

There is a compressive residual stresses in 3/10 of the length of the specimen. This distribution was compared with others distributions found numerically by others authors **[3, 4]**, our results show a good concordance.

5.4. Traction with expansion

In this case, we used a variety of traction load: 14 KN, 20 KN and 28 KN with the presence of the residual compressive. The variation of the stress obtained for the three cases was compared with the case of the traction load of 28 KN without the presence of residual compressive stresses. Figure 6 show this comparison.

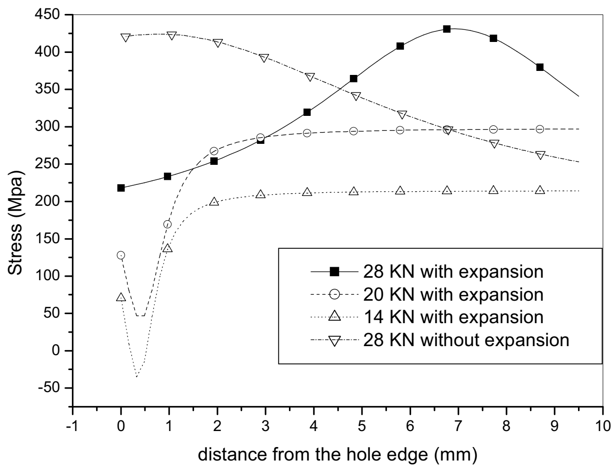

Figure 6: Comparison of the stress variation according the ligament of the specimen

This figure show the beneficial effect of the compressive residual stresses on the stress variation around the hole edge, we note that for the load of 28 KN and with the use of the cold expansion, the maximal stress was reduced with a percentage of 44%. So, in this case the zone of the stress

concentration was displaced to specimen edge. For the 20 KN load, we note that, in the two milimeter of the hole edge, there is no a stress concentration. The last cases of load (14 KN) present an optimal distribution of the stress with any area of stress concentration.
To conclude, the stress distribution is a resultant of the stress due to the traction and the compressive residual stresses.

5.5 Effect of the residual compressive stresses on the stress concentration factor

The stress concentration factor was compared for the three cases of load for a hole wiyh and without cold expansion. The Neuber's relation was used to calculate this factor

$$K_T^2 = K_\sigma . K_\varepsilon \tag{1}$$

with

$$K_\sigma = \frac{\Delta\sigma}{\Delta\sigma_N} \tag{2}$$

and

$$K_\varepsilon = \frac{\Delta\varepsilon}{\Delta\varepsilon_N} \tag{3}$$

$\Delta\sigma$ et $\Delta\varepsilon$: respectivelly the stress and the local strain amplitude.
$\Delta\sigma_N$ et $\Delta\varepsilon_N$ respectivelly the nominal stress and strain amplitude.
the calculated values of the stress concentration factor was registered in table 1

Traction load (KN)	K_T	
	without expansion	with expansion
28	1.45	1.37
20	2.85	1.31
14	2.91	1.33

Table.1 : Calculated values of K_T

For the not cold expanded holes, the values comparison show that the compressive residual stresses reduce the values of the stress concentration factor (reduction of 5.5% for the case of 28 KN and 54% for the others cases of load). This percentage difference is due to the high plasticization caused by the 28 KN load which was reduced the stress concentration factor.
In addition, for the specimen without expansion, we notices that the stress concentration factor is inversely proportional to the load, that is explained by made that for the high loads we have more plastic deformations and a larger size of the plastic zone. Thus part of the energy stored by specimen will be dissipate by the plastic slips and consequently the stress concentration decreases, this by supposing that the plasticized zone does not present any cracks. Concerning the values of K_T of the specimen which hole was cold expanded, they are very close, therefore an increase in the

load does not influence the concentration factor of constraints since these specimen are already plastically deformed in the vicinity of the hole by the expansion process which will be decreases the stress concentration factor.

5.6. Effect of the compressive residual stresses on the stress intensity factor

With end to analyze the effect of the residual stresses on the stress intensity factor, we created a crack in the vicinity of the hole of 1 mm length (Figure 7)

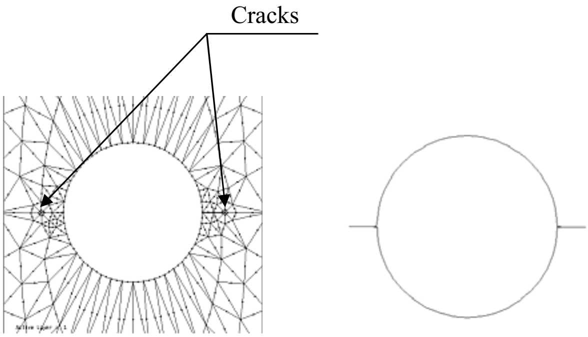

Figure 7 : Cracks in the hole edges

With end to ensure a good reading of the curves, we preferred to separate them, figures 8, 9 and 10 respectively show the variation of the stress intensity factor at the head of crack according to its length for the loads 14 kN, 20 kN and 28 kN with and without expansion of the hole.

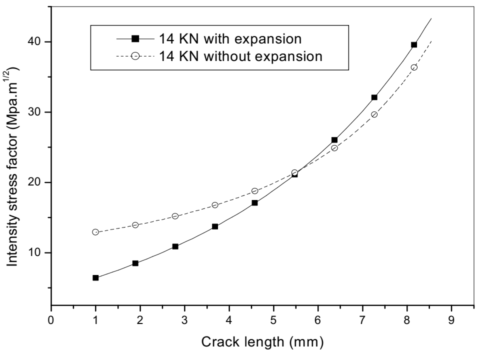

Figure 8: Variation of the stress intensity factor according the crack length (14 KN)

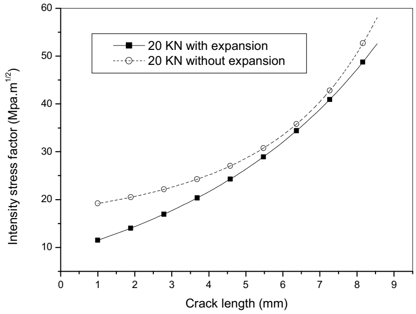

Figure 9:Variation of the stress intensity factor according the crack length (20 KN)

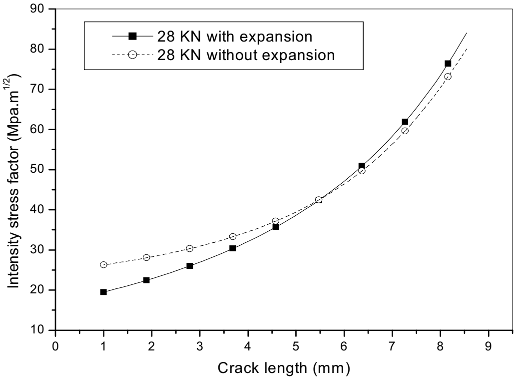

Figure 10: Variation of the stress intensity factor according the crack length (28 KN)

According to these figures, the three loading cases present the same behaviour where it is noticed that the stress intensity factor increases with the increase length of crack.
The effect of the compressive residual stresses was quite clear on the stress intensity factor in the first millimetres of the vicinity of the hole where it is noticed that the presence of these stresses in this zone makes reduce the stress intensity factor, thing which makes decrease the speed of the cracks and delay their propagation in the event of cycle of traction repeated. This reduction is estimated at the head of crack before propagation of 55% for the load of 14 kN, 42% for a load of 20 kN and 28 % for the load of 28 kN.
From the third millimetre of the vicinity of the hole, the two curves (expansion and without expansion) start have to approach gradually and follow almost the same trajectory because the plasticized zone due to the compressive residual stresses is extended on 3 millimetres from the edge of the hole, therefore these compressive residual stresses start gradually lose their effect from the third millimetre of the hole edge.
This deduction was compared with other work recently published which shows that the residual stresses reduced the stress intensity factor **[5]**.

6. Conclusion

Through this numerically study we could illustrate the effect of the compressive residual stresses on the stress variation in the hole edges for a case of uniaxial loading of traction, we also could see the influence of these residual stresses on the stress concentration factor .aints.

A beneficial effect of the residual stresses was noticed on the stress distribution in the vicinity of the hole for two values of the load of traction (14 kN and 20 kN) while for the third values of load (28 kN), a modification was noticed in the stress distribution where the stress concentration zone was moved far towards the end of specimen.

In addition, we could deduce that the compressive residual stresses reduce the values of the stress concentration factor.

Another beneficial effect of the residual stresses was also observed in the presence of crack where a reduction in the stress intensity factor was observed. Thus in the event of fatigue cycle, this reduction gives a high fatigue life since it makes weaken the cracks speed and delay the propagation.

In general the compressive residual stresses do not always presents a beneficial effect on material, a great plasticization can weaken material and decrease its fatigue life.

Thus it is necessary to optimize the gradient of residual stresses according to material loading in order to balance to the maximum the stress loading and the compressive residual compressive stresses, that is not an easy work especially in the complex cases where several multiaxial loadings intervenes.

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