NUMERICAL ANALYSIS REVEALS COLD EXPANSION'S INFLUENCE ON RIVET HOLE STRESS AND J-INTEGRAL VALUES

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ABSTRACT*: In the aeronautical construction several rivet holes are drilled, these holes constitute stress concentration zones which can be affects the fatigue life through cracks initiation at the edge of rivet holes. To remedy this problem and minimize stress level in these zones, the cold expansion technique is used to enhancing the fatigue life of rivet holes. The present work aims to investigate through finite element analysis the effect of three degree cold expansion (2%, 4.5% and 6%) on the reduction of stress level on the edge of rivet hole. The hole-crack interaction effect was thus analyzed. This effect is quantified by the values of J-Integral at the two tip of crack. The obtained results show that negative values of J- Integral was found which can be explained by the beneficial effect of residual compressive stresses induced by cold expansion on the crack closing.*

KEYWORDS*: Rivet holes; cold expansion; residual stresses; crack; J-Integral*

1 INTRODUCTION

Aluminum alloys are still massively used in aeronautical structures mainly because of their low density. The design of such structures must take into account the stresses of flight as well as the risks of damage in service. The assembly constraints of the different parts composing a structure generally show important concentrations within the material. Indeed, although welding is nowadays introduced within the structure of an aircraft, the assembly by riveting still represents 95% of the junctions where the totality of the critical parts. The holes thus introduced into the structure are present a zone of high stress concentration from which fatigue cracks can be initiated and propagate. Many researchers have attempted to develop appropriate techniques for reducing the risk of fatigue cracking in these holes. The cold expansion process has been used for many years as a standard technique to delay the initiation and propagation of fatigue cracks [1–4]. To achieve cold expansion of the hole, an oversized conical pin is forced into the hole, which plasticizes its contour. After the pin has passed through the diameter of the hole, the elastic return of the material surrounding the hole creates residual compressive stresses. The service load must overcome the compressive residual stress before the crack can initiate and then grow, thus leading to a longer fatigue life [4-6]. Almost all of the investigations conducted in the past on the cold expansion process have focused on a hole in the center of a plate with adequate distance from the plate free edges [2–9]. Since in many practical cases, the holes have to be drilled near the edge of a sheet, there are concerns about the residual stress distribution around such holes and its effects on the cold expansion results. Indeed, for holes with small edge distance ratios, unconstrained plastic deformation in the ligament near the free edge may relieve the beneficial residual stresses. Edge distance is usually defined by the ratio of the distance between the hole center and the free edge of the plate and the diameter of hole.

The present work aims to investigate through finite element analysis the effect of three degree cold expansion (2%, 4.5% and 6%) on the reduction of stress level on the edge of rivet hole. The hole-crack interaction effect was thus analyzed. This effect is quantified by the values of integral-J at the two tip of crack. The obtained results show that negative values of J-Integral was found which can be explained by the beneficial effect of residual compressive stresses induced by cold expansion on the crack closing. Therefore, the purpose of this study is to investigate how a reduction in the edge distance ratio of the distance between the hole center and the free edge of the plate and the diameter of hole may affect the residual stress distribution around a cold expanded hole. To separate the influences from different factors, and to identify the parameters that may have an effect on the improvement of life time, a two-dimensional non-linear finite element analysis is employed for investigating the evolution of the residual stresses around the hole edge in a plate of Al 2024 alloy.

Various degrees of cold expansion (DCE) are used (2%, 4.5% and 6%). In addition to various edge distances ratios are considered in the finite element simulation.

2 MATERIAL PROPERTIES

The material used in this study is an AERO TL 2024-T3 aluminum alloy used specifically for aircraft construction. The mechanical properties of this alloy are listed in Table 1.

Tab.1. Material property [19].

Ultimate strenght [MPa]	Yield strenght [MPa]	Metal T Displacement [%]	Elastic modulus [GPa]	Poisson's ratio
452	280	18.1	69	0.33

Law of material behavior

The behavior of the alloy 2024-T3 is obtained by a tensile test; figure 1 shows the average tensile curve (stress-strain) of the material.

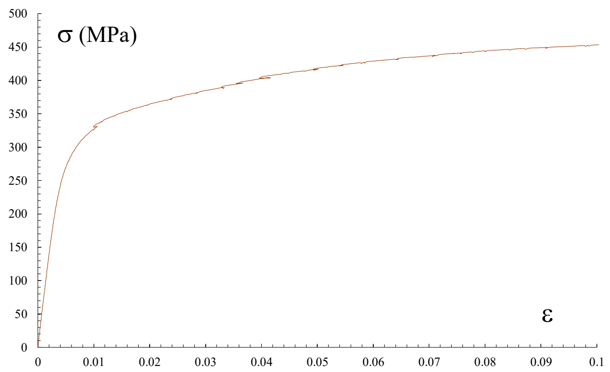


Fig.1. Average tensile curve for aluminum alloy 2024-T3 (stress - strain) [7]

3 GEOMETRICAL MODEL

In this work, we consider a rectangular plate made of 2024-T3 aluminum alloy with the following dimensions: length H = 150mm, width W = 50mm and thickness e = 2mm. This plate contains a central hole of 6 mm of diameter (Figure 2).

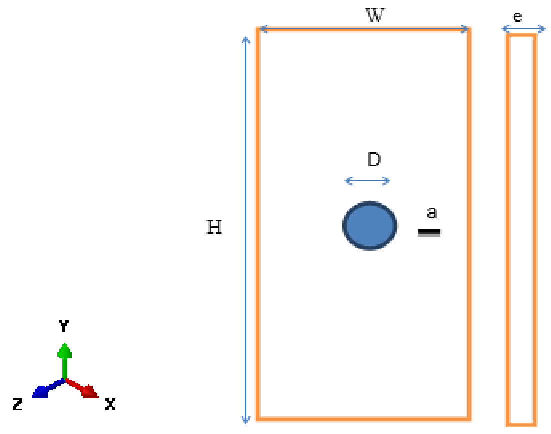


Fig.2. Geometric model.

4 MESHING AND BOUNDARY CONDITIONS

The figure 3 shows the plate meshing and the boundary conditions, the plate is totally embedded on one side and supports a tensile load on the other side. A hexahedral element (quadratic element - C3D20R) was used for meshing; the total number of elements is 19260 and the number of nodes is 24024. The mesh is refined around the hole and at the cracks tips.

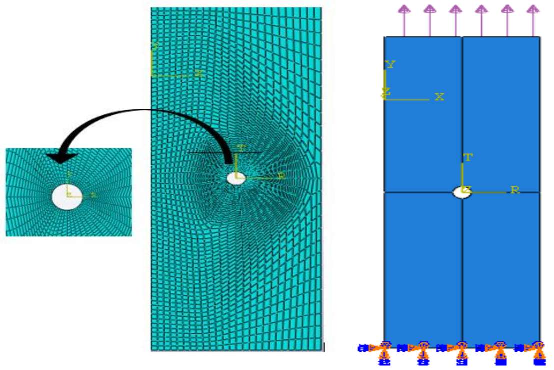


Fig.3. Plate meshing and boundary conditions

5 METHODOLOGY

In a first step of this work, we will analyze the variation of stresses according the plate ligament for different applied tensile loads: 10 MPa, 30 MPa and 50 MPa. Subsequently, and in order to know the level of residual compressive stresses induced by the process of cold expansion of the hole, we will simulate this process for three degrees of expansion : 2% ; 4.5% and 6%. The beneficial effect of these residual stresses on the reduction of the applied tensile stress level is shown by a new analysis of the stress variation along the plate ligament. Finally, the effect of the presence of a crack near to the hole is analyzed; the effect of the crack length and its position is illustrated through the values of the J-Integral.

6 RESULTS AND DISCUSSION

6.1 Stress variation according the plate ligament for different applied tensile loads

Figure 4 give us an idea about the level of the maximal stress in the hole edge for the applied tensile loads (10 MPa ; 30 MPa and 50 MPa).

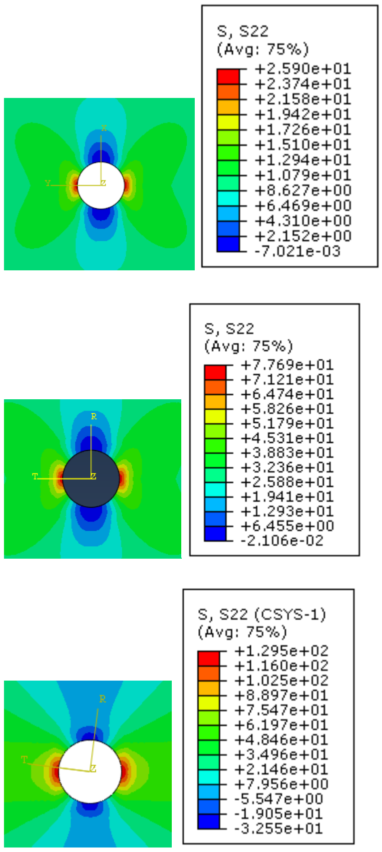


Fig.4. Stress level in the hole edge for different tensile loads a) 10 MPa, b) 30MPa and c) 50 MPa

Figure 5 describe the stress variation according the plate ligament for different applied tensile loads.

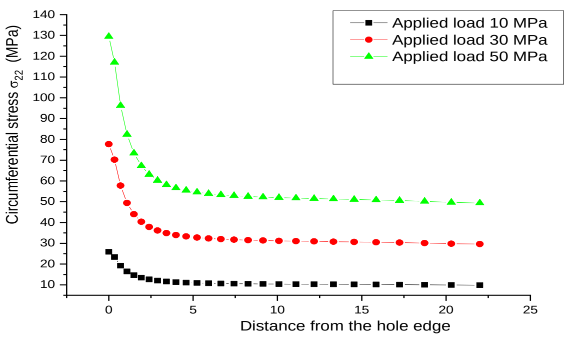


Fig.5. Stress variation according the plate ligament for different applied tensile loads

We can see that the stresses are maximal at the edge of the hole, moving away from the hole edge the stresses decrease. This is due to the notch (hole) which amplifies the value of the applied stress, far from this notch the stress concentration disappears.

6.2 Simulation of the hole cold expansion process

To simulate the hole cold expansion process, a displacement was imposed on the inner contour of the hole. This displacement is calculated using the equation 1[8] in such a way that is corresponding in each case to one of the three degrees of expansion (2% ;4.5% ;6%)

$$DCE\% = \frac{\mathrm{D} - \mathrm{d}}{\mathrm{d}} \mathrm{x100} \qquad (1)$$

DCE: Degree of cold expansion
D: Diameter of the tapered pin
d : Diameter of the hole

The interference between the diameter of the hole and that of the cylindrical part of the pin can vary between 2% and 6% [9, 11]. Above 6% there is a risk of damaging the material.

Figure 6 shows the imposed displacement at the inner contour of the hole.

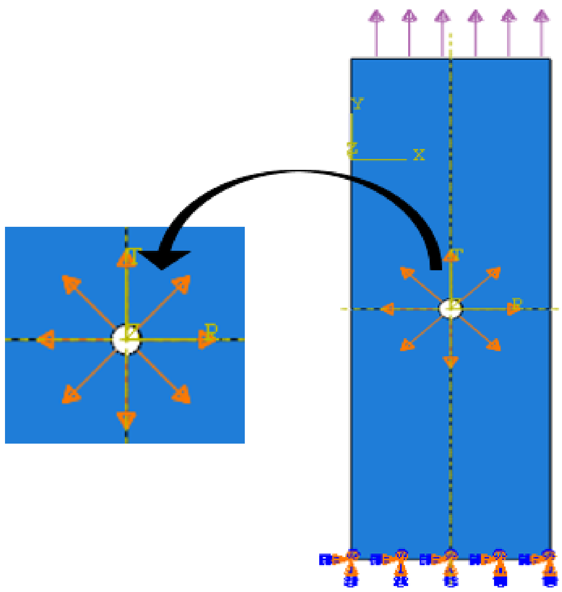
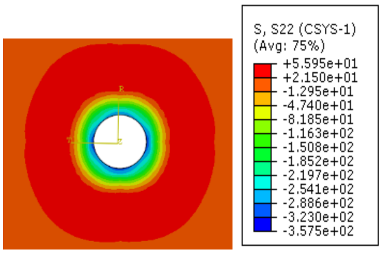
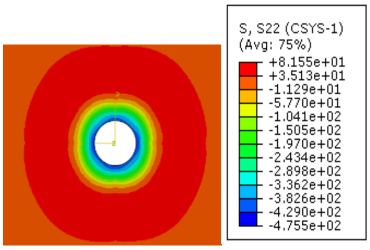


Fig.6. Hole Plate with expansion and applied load

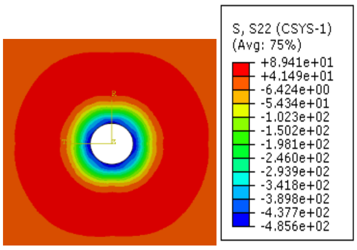
Figure 7 shows the level of compressive residual stresses obtained after the cold expansion for the three degree.



DCE = 2%



DCE = 4.5%



DCE = 6%

Fig.7. Compressive residual stress level obtained for the three degree of cold expansion

We note that for a degree of cold expansion 2% (DCE 2%), the maximal compressive residual stress is -375 MPa while for 4.5% is -475 MPa and for 6% is -485 MPa. So an increase of 2.5% in the degree of cold expansion results in the increase of the maximal compressive residual stress of 26.66 % while an increase of 4% leads to an increase of the maximal compressive residual stress of approximately 30%.

The variation of the compressive residual stresses induced by cold expansion according the plate ligament is shown in figure 8.

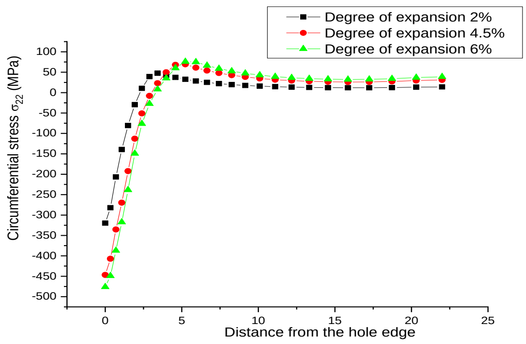
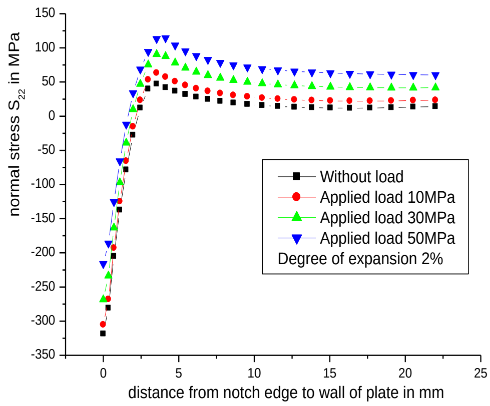


Fig.8. Variation of compressive residual stresses induced by cold expansion according the plate ligament

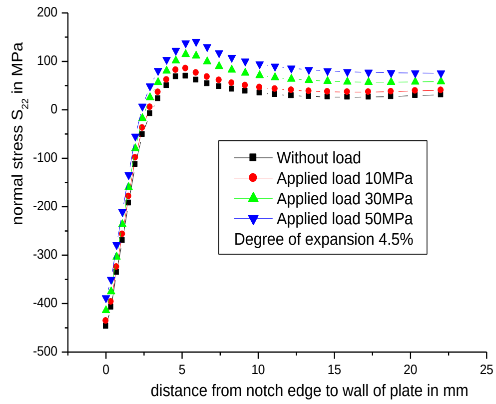
As indicated in figure 8, the residual compressive stress values are significant within the first two millimeters of the hole edge. Moving away, compressive residual stress decrease significantly, more and more as we approach the plate edge, the compressive residual stresses reachs a value of zero.

6.3 Stress variation according the plate ligament

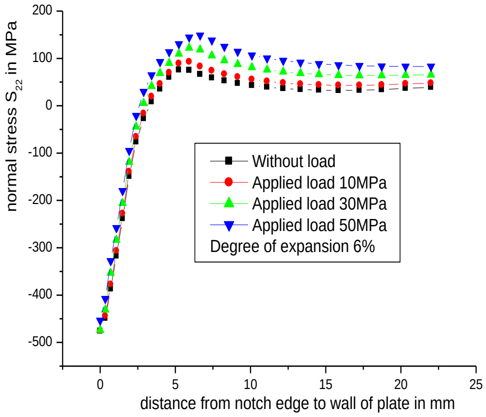
Stress variation according the plate ligament for different applied tensile loads with the presence of compressive residual stresses. Figure 9 shows the compressive residual stress relaxation due to the applied tensile loads, this relaxation is relative to the level of these applied loads.



DCE 2%



DCE 4.5%



DCE 6%

Fig.9. Stress variation according the plate ligament for different applied tensile loads with the presence of compressive residual stresses

By comparing with figure 5, we can clearly see the beneficial effect of compressive residual stresses on the reduction of stress concentration in the hole edge which makes it possible to use even higher tensile loads without risk of stress concentration.

6.4 Effect of interaction hole – crack on the stress variation

In this case of study, we consider a crack of 2mm of length positioned along the half width of the plate between the hole and the free edge of the plate, firstly the crack is located at 10 mm from the hole edge and at 10 mm from the plate edge (Figure 10), then after we consider a variable position of the crack. The objective is to analyze the effect of the crack position on the relaxation of compressive residual stresses on the opening or the closing of this crack. This effect is quantified by the values of J-Integral at the two tip of crack. With the crack presence, the plate meshing has been modified. The number of elements will be 29690 and the nodes number will be 36900, a rosette is created at the two tips of the crack. Hexahedral elements of type C3D20R were used with a mesh refinement at the hole contour and at the crack's tips (Figure 10).

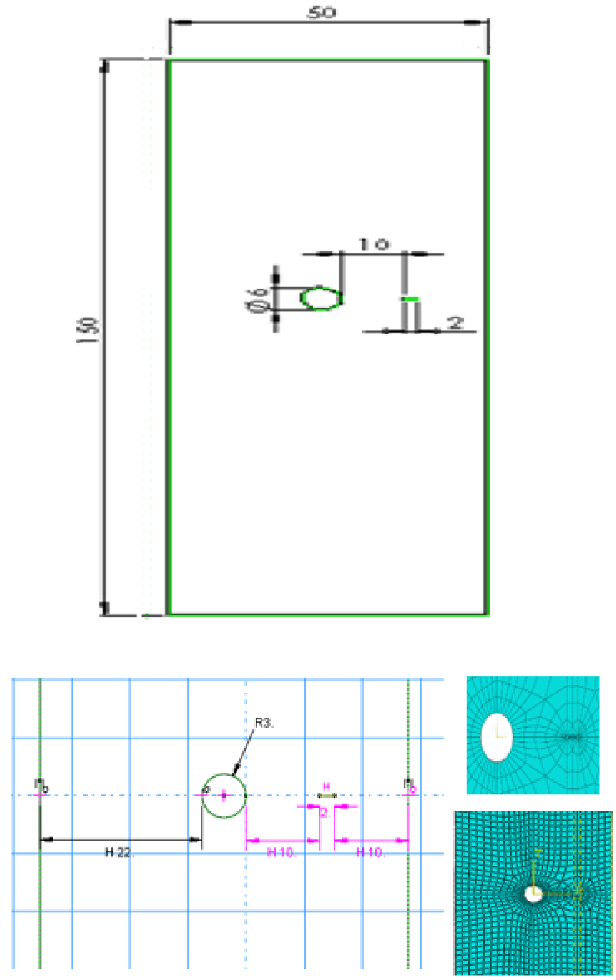
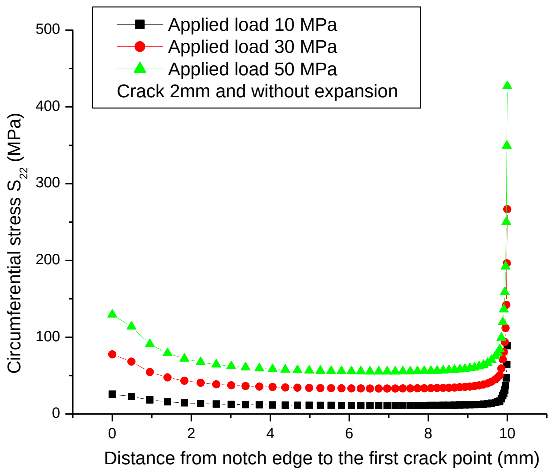


Fig.10. Plate meshing with two notches (Hole – crack)

Figure 11 shows the stress variation near the hole and near the two crack tips for different applied loads without taking into account the effect of compressive residual stresses.



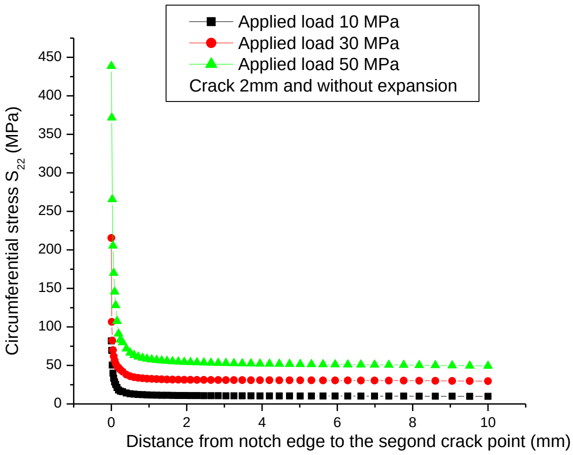


Fig.11. Stress variation according the plate ligament for different applied loads without expansion (hole edge– crack's tips)

according to this figure we can see that the stress concentration is much higher in the two crack tips specially for tensile load of 50 MPa where the stress value at the crack tip is three time bigger than the stress value in the hole edge.

Effect of the crack position on the level of stress concentrate

Without cold expansion effect

In order to see the effect of the crack position on the stress concentration level we will change its position from the hole edge, four positions are used: 0.5 mm; 2 mm; 5 mm and 10 mm. Figure 12 shows the stress level for a crack position of 0.5 mm for two applied loads 10 MPa and 50 MPa.

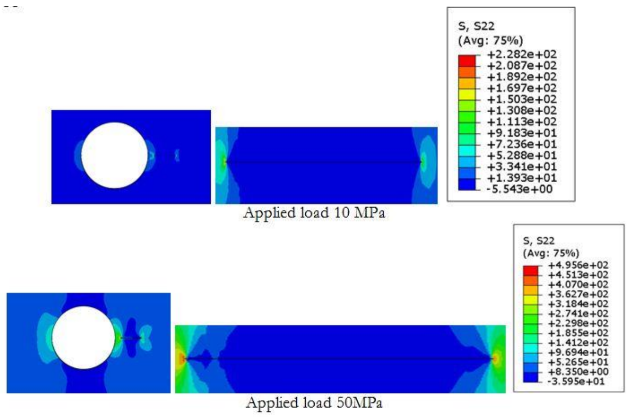


Fig.12. Stress concentration level for a crack position of 0.5 mm

From Figure 12, it can be seen that for an applied load of 10 MPa, the stress concentration is maximum at the first crack tip. With increasing the load to 50 MPa, the stress concentration becomes located at the second crack tip where the maximum stress value reaches approximately 465 MPa. The stress concentration level in the first crack tip (adjacent to the of the hole edge) has been slightly reduced due to the interaction between two plasticized zones (hole edge - first crack tip)

Figure 13 shows the stress level for a crack position of 2 mm for two applied loads 10 MPa and 50 MPa.

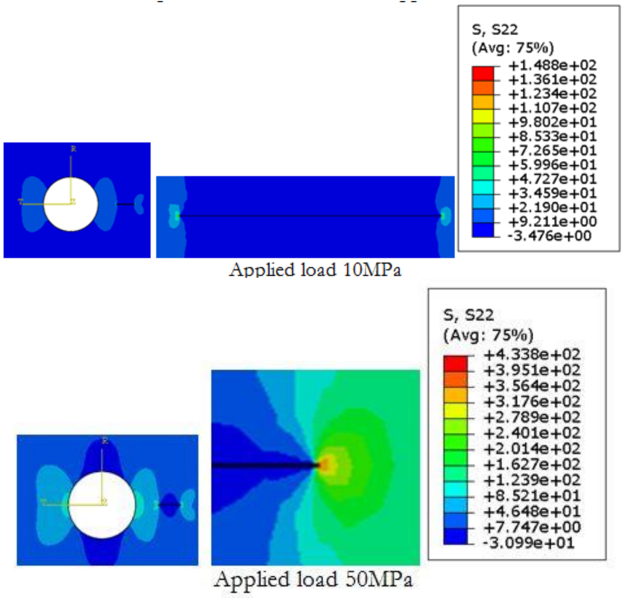
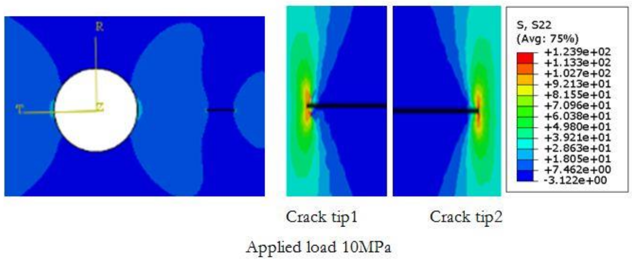


Fig.13. Stress concentration level for a crack position of 2 mm

Compared to the first case (crack position of 0.5 mm), we note that by moving away the crack from the hole edge by 2 mm and for an applied load of 10 MPa, it can be seen that the level of stress concentration in the first crack tip is reduced by 34%, whereas the stress concentration in the second crack tip has increased by 38%. For an applied load of 50 MPa the stress level is reduced in the first crack tip by 8.5% and in the second crack tip by 5%.

Figure 14 shows the stress level for a crack position of 5 mm for two applied loads 10 MPa and 50 MPa.



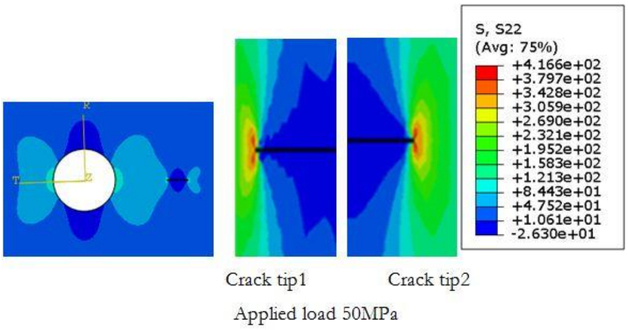


Fig.14. Stress concentration level for a crack position of 5 mm

For a crack position of 5 mm from the hole edge, we can see that the stress concentration is localized at both crack tips. The maximum stress value reach approximately 420 Mpa, this value is enregistred in the second crack tip.

Figure 15 shows the stress level for a crack position of 10 mm for two applied loads 10 MPa and 50 MPa

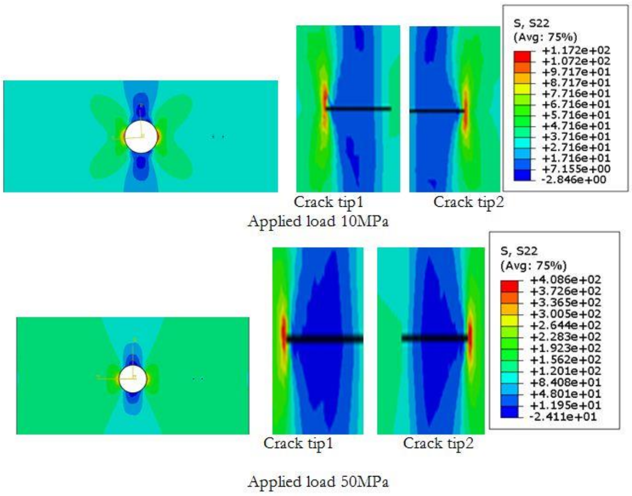


Fig.15. Stress concentration level for a crack position of 10 mm

In this case where the crack is positioned in the center of the distance between the hole edge and the plate edge. For the two applied loads, the stress concentration is noticed at both crack tips with nearly symmetric repartition.

Finally, we can deduce that moving the crack away from the hole edge reduces the stress level at both crack tips.

With cold expansion effect

Figure 16 shows a comparison of the distribution of compressive residual stresses induced by cold expansion process according the plate ligament for the three degree 2% ; 4.5% and 6% (without applied load).

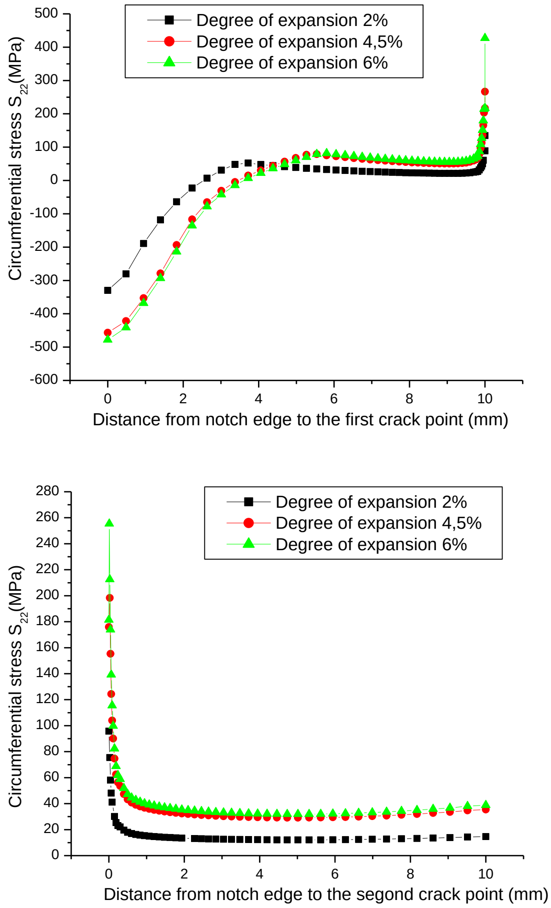
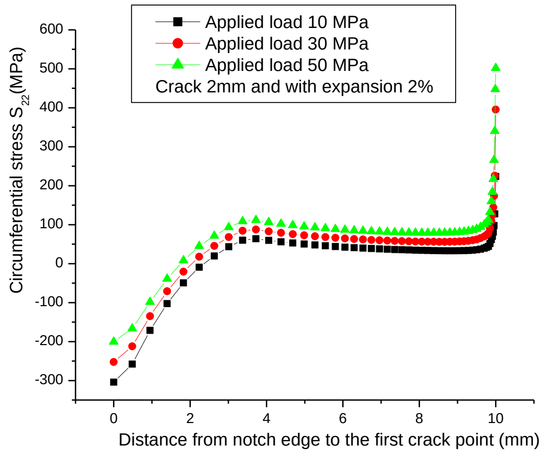


Fig.16. Distribution of residual stresses induced by cold expansion according the plate ligament with crack length of 2 mm poisoned at 10 mm from the hole edge.

Figure 17 shows the stress concentration level for a crack length of 2 mm positioned at 10 mm from the hole edge for the case of three applied loads 10 MPa, 30 MPa and 50 MPa with the presence of the residual stress induced by cold expansion process of 2%.



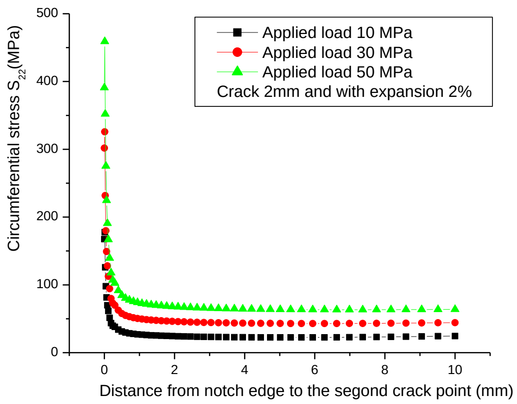
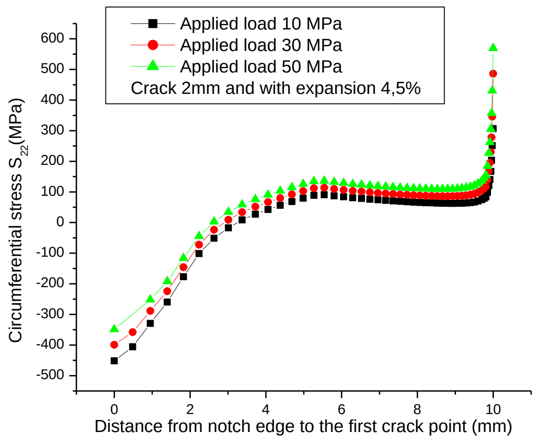


Fig.17. Effect of residual stresses induced by cold expansion on the stress concentration level (crack length 2 mm poisoned at 10 mm from the hole edge) DCE 2%

Figure 18 shows the stress concentration level for a crack length of 2 mm positioned at 10 mm from the hole edge for the case of three applied loads 10 MPa, 30 MPa and 50 MPa with the presence of the residual stress induced by cold expansion process of 4.5%.



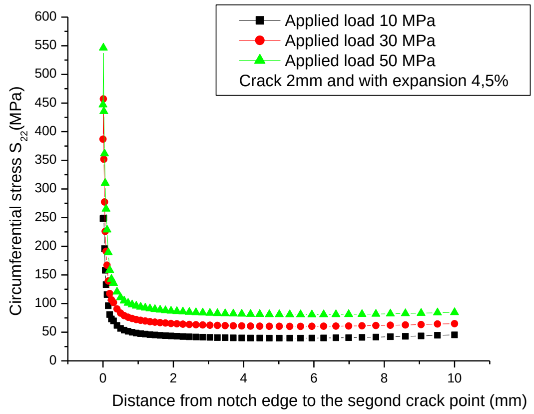
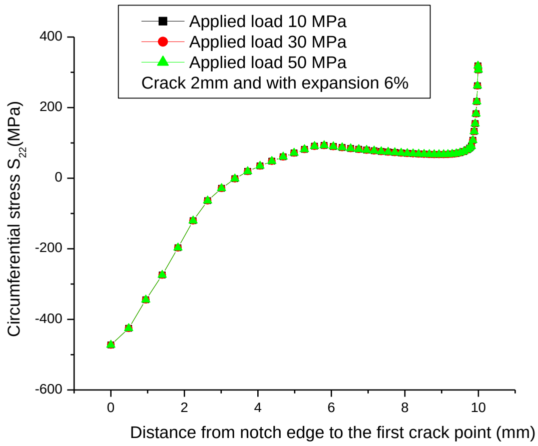


Fig.18. Effect of residual stresses induced by cold expansion on the stress concentration level (crack length 2 mm poisoned at 10 mm from the hole edge) DCE 4.5%

Figure 19 shows the stress concentration level for a crack length of 2 mm positioned at 10 mm from the hole edge for the case of three applied loads 10 MPa, 30 MPa and 50 MPa with the presence of the residual stress induced by cold expansion process of 6%.



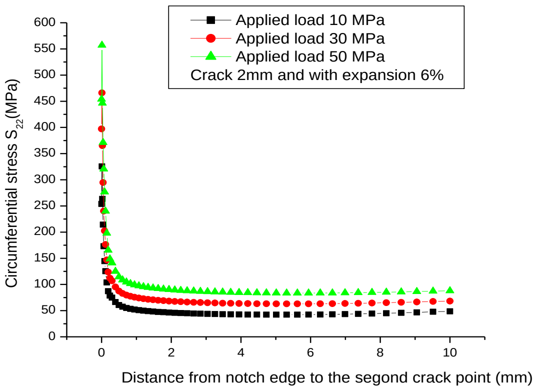
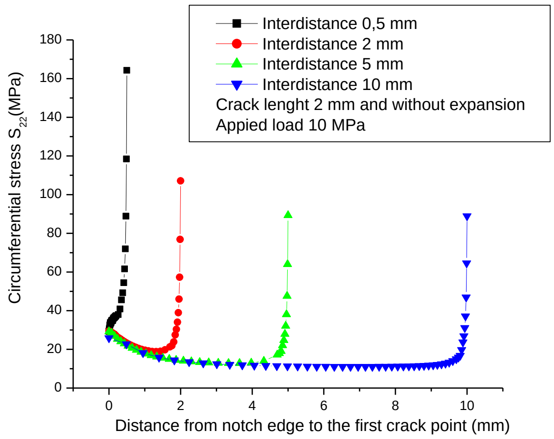


Fig.19. Effect of residual stresses induced by cold expansion on the stress concentration level (crack length 2 mm poisoned at 10 mm from the hole edge) DCE 6%

Figure 20 groups the results concerning the stress distribution along the plate ligament for different crack positions and for an applied load of 10 MPa and 50 MPa.



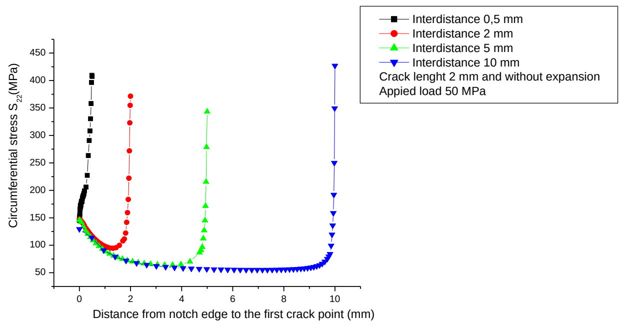


Fig.20. Effect Stress distribution according the plate ligament for different crack position. a) Applied load 10 MPa b) Applied load 50MPa

Variation of J-integral

In order to show the effect of the compressive residual stresses on the variation of the values of the J-integral we will proceed to the calculation of the values of the J-integral with and without the presence of the effect of the cold expansion of the hole. Figure 21 shows the crack length for a position of 10 mm from the hole edge.

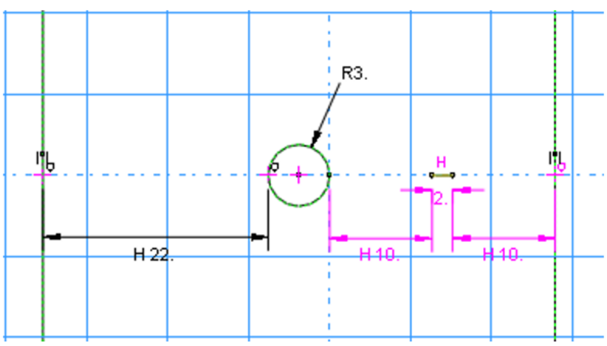


Fig.21. Crack length and position from the hole edge and the plate edge

Effect of applied load (without expansion)

The following figure shows the J-integral values for the first crack Tip near the notch (hole) for an applied load of 10 MPa and 50 MPa (without cold expansion process)

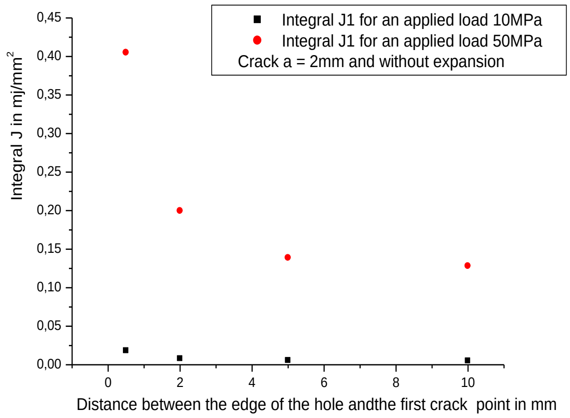


Fig.22. Variation of the J-integral values according the plate ligament without cold expansion effect

From this figure, we notice the following:

- Moving away from the notch (hole edge), the values of the J-integral decrease.
- Increasing the load from 10 MPa to 50 MPa increases the values of the J values.
- Under these conditions, a high load can lead to a brutal rupture of the part.

From figure 23, It is noticed that the value of the integral J at the point of crack 1 is more important than that of the point of crack 2 since it is close to the notch and increases with the applied load. Far from the notch the value of the j-integral is low and a slight difference is noted if the applied load increases. On the other hand, if the crack is close to the notch, a considerable increase is to be noted in the value of the integral-J. If the applied load is low, the position of the crack does not have a great influence on the value of the j-integral.

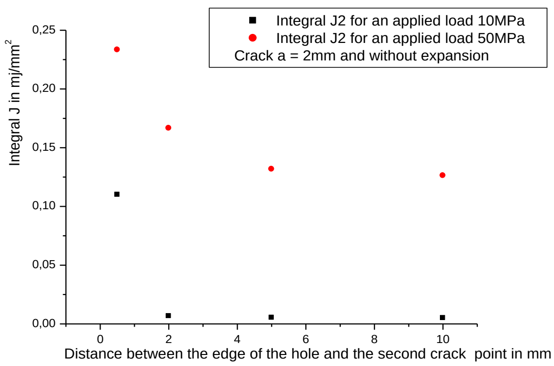


Fig.23. Variation of the J-Integral values according the plate ligament without cold expansion effect.

The same remark should be noted for the crack tip 2, where the value of the J-Integral varies with the position of the crack. If the crack is far from the free-edge of the plate the value of the integral-j decreases.

The values of the j-integral at the level of the head of crack 2 are a bit low compared to the value of the j-integral at the level of the level of the head of crack 1 since the concentration of stresses due to the presence of the notch is higher than that of the free edge.

J-Integral with presence of hole expansion

Figure 24 shows the variation of the values of the j-integral in the presence of compressive residual stresses for a degree of expansion of 2%.

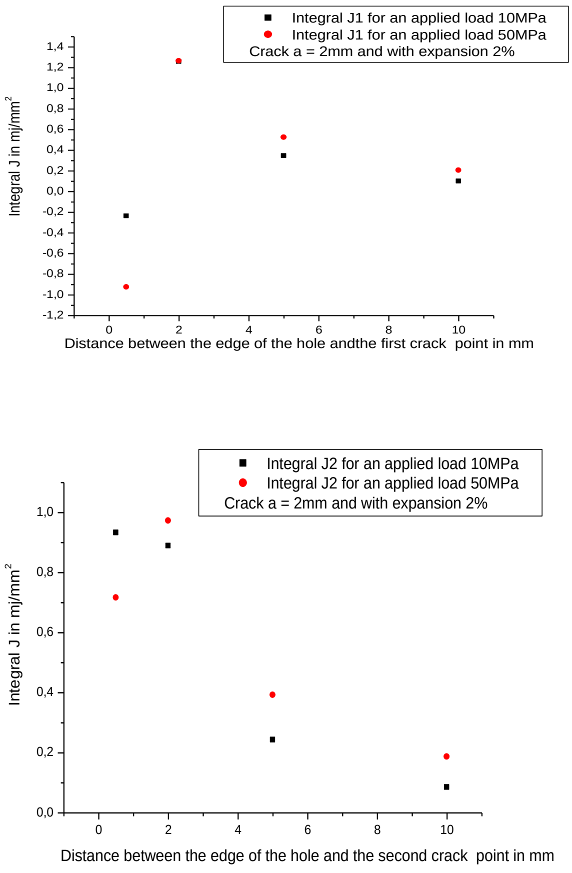


Fig.24. Variation of the J-integral values according the plate ligament for DCE of 2%; a) for crack tip1 and b) for crack tip2.

From this figure, we can see that:

- The values of the J-integral in the first millimeter of the hole edge are negative which shows the beneficial effect of the compressive residual stresses resulting in a crack closure phenomenon and thus a higher fatigue life.
- Even at a load of 50 MPa, the J-integral values are negative.
- By moving away from the first millimeter of the hole end, the J-integral values were reduced by 50% while comparing with the case without expansion.

However, for the crack point2, the value of the J-Integral2 increases compared to the case without expansion, and the value of the J-integral increases if the crack point is close to the free edge of the plate. For these positions, the crack is always in the positive stress field

The following figures (25- 26) shows respectively the variation of J-integral for DCE of 4.5% and 6%. Comparing with the case of DCE of 2% (Figure 23),

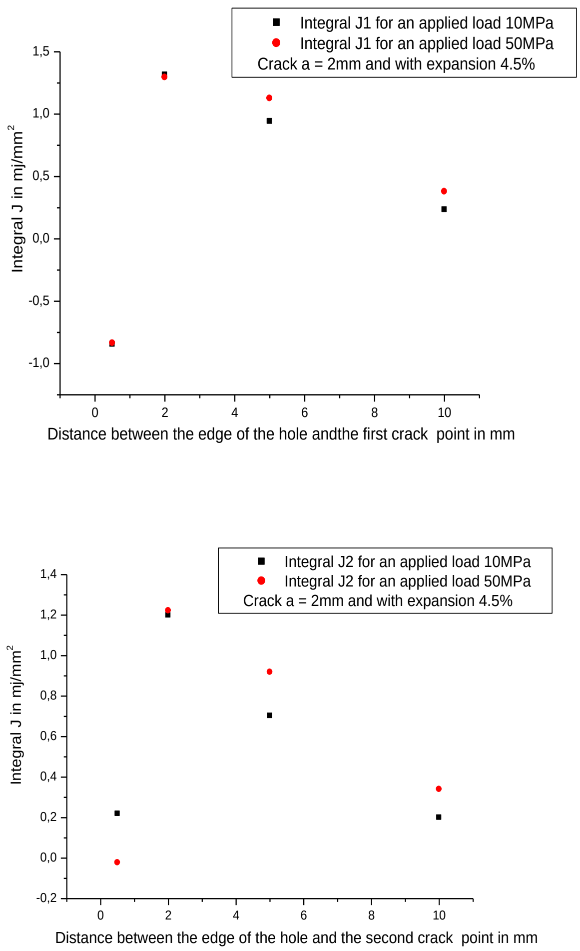
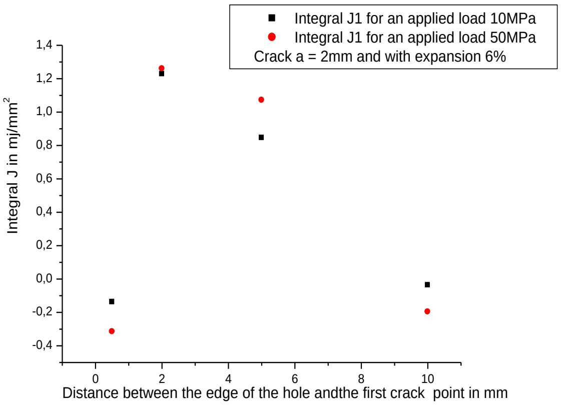


Fig.25. Variation of the J-integral values according the plate ligament for DCE of 4.5%, a) for crack tip1 and b) for crack tip2



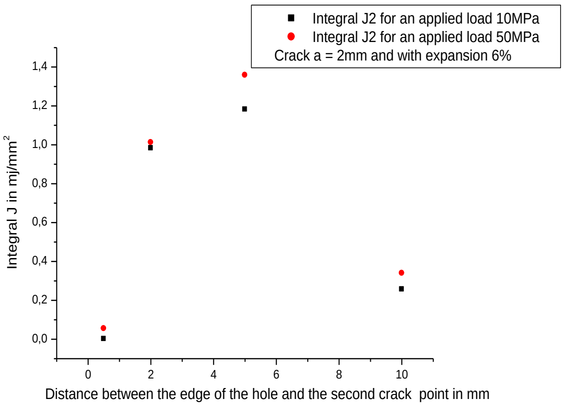


Fig.26. Variation of the J-integral values according the plate ligament for DCE of 6 %.

According these figures, we see that:

- Increasing the degree of cold expansion (DCE) slightly increases the values of the J-integral
- Increasing from 2% to 4.5% increases the J-integral values in the first millimeter of the hole edge by 70%. This is explained by the size of the plastic zone caused by the expansion process depending on the degree used

In the same way for the point of crack 2, while approaching the zone of compression the value of the J-Integral decreases to be almost null. Away from the notch, the J-integral at crack point 2 becomes small and increases slightly with increasing applied stress. if the point of crack 2 moves away from the notch, a decrease in the value of the integral-j is noted.

7 CONCLUSION

The aim objective of this work was to investigate through finite element analysis the effect of three degree cold expansion (2%, 4.5% and 6%) on the reduction of stress level on the edge of rivet hole and to analysis the hole-crack interaction effect. The obtained results led us to draw the following deductions:

- The residual stresses induced by the cold expansion process have a beneficial effect especially in the two first millimeters from the hole edge.
- An appreciable decrease in the values of J-integral was recorded in this area.
- The crack closure phenomenon was observed in the two first millimeters by using a degree of cold expansion of 2%.
- A high cold expansion degree can lead to material damage and crack propagation.
- Concentration stresses are maximal at the hole edge, moving away the stresses decrease. This is due to the notch (hole) which amplifies the value of the applied stress, far from this notch the stress concentration disappears.
- The maximum compressive residual stress obtained with cold expansion degree of 2% is -375 MPa while for 4.5% is -475 MPa and for 6% is -485 MPa.
- In the presence of a crack according the plate ligament, stress concentration is much higher in the two crack tips specially for tensile load of 50 MPa where the stress value at the crack tip is three time bigger than the stress value in the hole edge.
- For a crack position of 0,5 mm from the hole edge and for an applied load of 10 MPa, the stress concentration is maximum at the first crack tip. With increasing the load to 50 MPa, the stress concentration becomes located at the second crack tip where.
- The stress concentration level in the first crack tip (adjacent to the hole edge) can been slightly reduced by to the interaction between the two plasticized zones (hole edge - first crack tip)
- Moving away the crack from the hole edge by 2 mm and for an applied load of 10 MPa, it can be seen that the level of stress concentration in the first crack tip is reduced by 34%, whereas the stress concentration in the second crack tip has increased by 38%. For an applied load of 50 MPa the stress level is reduced in the first crack tip by 8.5% and in the second crack tip by 5%.
- For a crack position of 5 mm from the hole edge, we can see that the stress concentration is localized at both crack tips.
- In this case where the crack is positioned in the center of the distance between the hole edge and the plate edge, for the two applied loads, the stress concentration is noticed at both crack tips with nearly symmetric repartition.

- Moving the crack away from the hole edge reduces the stress level at both crack tips.
- Moving away from the notch (hole edge), the values of the J-integral decrease.
- Increasing the load from 10 MPa to 50 MPa increases the values of J-integral, a high load can lead to a brutal rupture of the part
- The values of the J-integral in the first millimeter of the hole edge are negative which shows the beneficial effect of the compressive residual stresses resulting in a crack closure phenomenon and thus a higher fatigue life.
- Even at a load of 50 MPa, the J-integral values are negative.
- By moving away from the first millimeter of the hole end, the J-integral values were reduced by 50% while comparing with the case without expansion.
  - Increasing the degree of cold expansion (DCE) slightly increases the values of the J-integral
  - Increasing from 2% to 4.5% led to increases the J-integral values in the first millimeter of the hole edge by 70%. This is explained by the size of the plastic zone caused by the expansion process depending on the degree used.

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