Visual Abstract

Numerical analysis and optimization of the residual stresses distribution induced by cold expansion technique

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ABSTRACT. This paper presents a numerical investigation about the influence of mandrel shape on residual stresses induced by the cold expansion procedure. Thus, ball and tapered pin are used for cold expanding the plate. As, the entrance face presents the lowest residual stresses throughout the hole thickness, we propose to solve this problem by varying the mandrel taper degree, instead of applying a double expansion. The obtained results show that the tapered pin is more suitable for the cold expansion. More, low taper increases the residual stresses at the entrance, reaching the values generated at the exit face.

KEYWORDS. Cold expansion; Fastener hole; Residual stress; FEM method; Taper degree.

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INTRODUCTION

The technique of cold expansion of the fastener holes has been used over the last decades [1]. Essentially, as an efficient technique, it was introduced to the aircraft industry by Boeing Company about 50 years ago to enhance fatigue lives of fastener holes [2; 3]. Since then, considerable efforts have been done to improve the fatigue lifetimes of such structures. In fact, actually the cold expansion is used on almost all commercial and military aircraft in the world because of its proven performance to prevent the initiation and crack growth. Thus, it provides long-term benefits such as an important gain in structural fatigue life and then consequent economies in maintenance and essentially the structural safety level is significantly improved. However, the effectiveness of the cold expansion process depends on the magnitude and the distribution of the induced compressive residual stresses around the expanded hole [1; 4]. Indeed, several researchers have concluded that the fatigue lifetimes of the cold expanded fastener structures increases by a factor of 3 to 10, and this depends on the amount of the induced compressive residual stresses [2;5;6]. In this context, a number of related parameters can interfere to maximize the expected result of the cold expansion. Primarily, Mention may be made about the type of the oversized tool used for expansion. So, the cold hole expansion is usually conducted using an oversized ball technique [6; 7; 8; 9; 10; 11] or a tapered pin mandrel technique [1; 12; 13; 14; 15; 16]. On this subject, Gopalakrishna and co-authors [8] experimentally studied and compared the cold expansion of holes in Al 2024 using a Split-sleeve with taper pin technique and a split-sleeve with a ball technique. They concluded that, the former technique yielded 200% greater fatigue life improvement than that of the latter. In any case, it is well known that the entrance face of the hole exhibits the lowest circumferential compressive stress. Therefore, this region will possess the least fatigue enhancement [3; 17]. This is confirmed by experimental tests on pristine test coupons which have shown that fatigue cracks in cold expanded holes frequently initiate from this location, see for example [12]. In the same way, several researches substantiate the susceptibility of the dominant effect of the interference degree of the cold expansion process [8; 18; 19; 20]. In this regard, the literature is unanimous on the fact that increasing the degree of expansion increases the lifetime of the holed structure see for example [18; 21]. These latter, among others, confirm the hypothesis that, it is the induced residual stresses which are the important parameter for the fatigue lifetime improvement. Nevertheless, Amrouche and co authors in [6] and recently Yongshou and co authors in [20] concluded that the degree of expansion did not influence the magnitude of compressive residual stresses but it has an influence on the size of the compressive residual stresses zone and the size of the plastic strain zone. To this is added the effect of friction between the mandrel and the hole surface, which was argued to have a local effect on the circumferential compressive residual stresses. Effectively, Yongshou and co authors in [20] have studied, numerically, the effect of the friction coefficient and they had found that the friction coefficient affects the radial residual stress around the maximum value and the circumferential residual stress near the hole edge. In the same context, Yuan [23] have confirmed experimentally and numerically the latter finding. So, according to [12; 15; 16; 22; 23], the residual stress distribution is not uniform throughout the plate thickness having a maximum compressive value around the mid-thickness position and a minimum value at the mandrel entrance face of the hole edge. As a consequence, fatigue cracks usually initiate at a location near the entrance face. In order to compensate for the problem of non-uniformity, several solutions were proposed. The most one is the double expansion, see [7; 16; 24; 25; 26]. A short time exposing to elevated temperature was also proposed by Chakherlou and Aghdam [27]. Early in 2004, Chakherlou and Vogwell proposed a novel method which creates a near-uniform compressive tangential residual stress around a fastener hole using a tapered pin with a mating tapered split sleeve [28; 29]. More then, a geometrical solution for the hole or the mandrel were proposed. For example, Jang and coworkers [30] proposed to apply a chamfer into the hole and Rana, Makabe and Fujiwara [31] used a quasi elliptical shaped pin mandrel to optimize residual stresses around the hole edge. The present work proposes to optimize the residual stress profile resulting by a cold expansion technique. For this purpose, we propose to vary the taper degree of the tapered pin mandrel and analyzing the effect of the expansion tool shape on the resulted residual stresses around the hole edge throughout the plate thickness. Thus, the selected mandrels shapes are the most common used, such as a rigid ball and a conical mandrel (tapered pin).

GEOMETRIES AND PROCEDURE

The main goal of this work is to analyze the effect of the mandrel shape on the effectiveness of the cold expansion method and then attempt to optimize the cold expansion by searching the appropriate geometry of the mandrel. The plate dimensions are presented in Fig. 1. The 6.32 mm thickness model corresponds to the model studied by Chakherlou and Vogwell [12] to allow comparison and validation of the results. Fig. 1 shows the dimensions of the plates, which contains the hole diameter to receive the cold expansion.

Thereafter, the study will be oriented towards the analysis of the residual stresses induced across the face of the hole and its vicinity by two types of mandrel, essentially a tapered pin technique and a ball technique as shown in Fig. 2a and Fig. 2b, respectively. For the tapered pin, different tapers are used to perform the cold expansion.

Geometries of the mandrels

In this work, two types of Mandrel are considered. On one hand, a rigid ball with a diameter D = 5.23mm (Fig. 3b), and on the other hand, a conical pin with a small diameter "d" equal to the initial hole diameter of the plates d = 5 mm and a large diameter "D" equal to D = 5.23 mm (Fig. 3a). Both mandrels give a same interference degree "i" defined by the relation:

$$i\% = \frac{D-d}{d} \times 100 \quad (1)$$

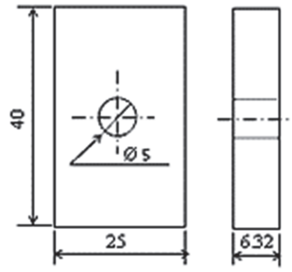
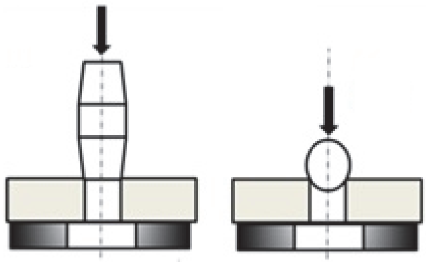


Figure 1: Geometry and dimensions of holed plate (Dimensions are in mm).



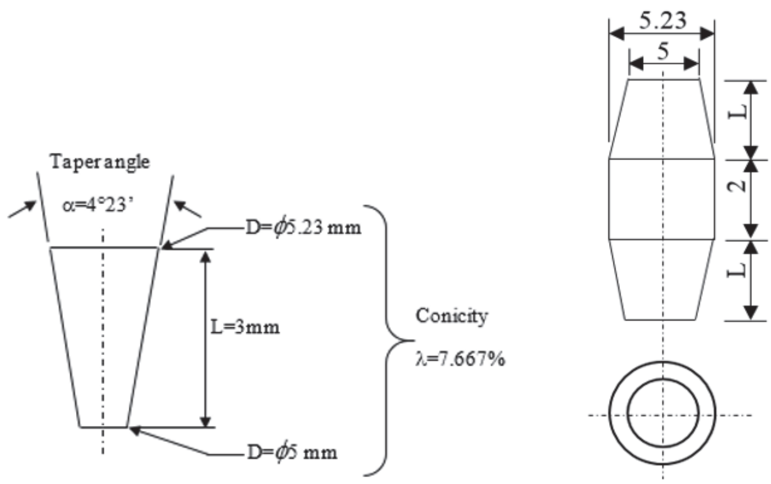
a) b)

Figure 2: Mandrels used for the expansion: a) rigid tapered pin and b) rigid ball.

In order to analyze the effect of taper parameters of the tapered part of the pin, we considered several cone lengths. Thus, the taper λ% parameter is calculated as follows:

$$\lambda\% = \frac{D-d}{L} \times 100 \quad (2)$$

where, L is the length of the tapered part as shown in Figs. 3a and 3b. Fig. 3a shows the geometric details of the tapered part of the mandrel. Thus for example, for L = 3 mm, the degree of taper λ = 7.667 %.



a) b)

Figure 3: Geometry definition of the tapered pin: a) Taper Details of the conical part of the pin mandrel, Case of L = 3 mm; b) Geometry and dimensions of the tapered pin.

Tab. 1 summarizes the different tapers used in this work corresponding to lengths L=2, 6, 8 and 10 mm as to be used in the presentation legend of the results.

L (mm)	Taper angle α	Taper λ %
2	6°35’	11.5
3	4°23’	7.667
6	2°12’	3.833
8	1°39’	2.875
10	1°19’	2.3

Table 1: Parameters of different tapered pin used in the study.

FINITE ELEMENT MODEL

A three dimensional finite element model was performed to simulate the cold expansion procedure. Thus, as already argued in [12], a 3-D model was preferred to the axi-symetric 2-D one because of rectangular plate shape and because it is easy to apply a longitudinal tensile load after cold expanding the plate. More even, the objective here is to analyze the residual stresses along the thickness of the hole. Abaqus 6.14 commercial finite element code was used to carry out this analysis. The finite element modelization for the plates and assembly sets are shown in Figs. 4. Fig. 5 shows the assembled sets for some studied cases.

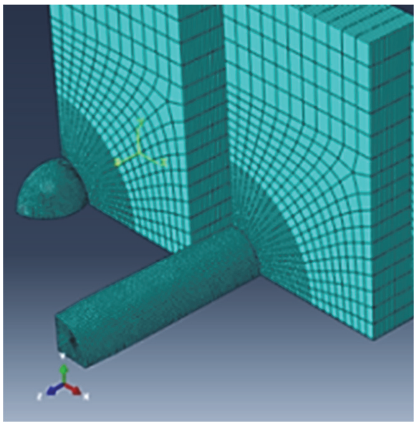


Figure 4: Finite element model for plate and assembly sets.

The studied models are symmetrical with respect to the X–Z and Y–Z planes; therefore only a quarter of these geometries were modeled. The hole diameter is 5 mm and the largest diameter of the tapered pin is 5.23 mm which produces a 4.6% interference fit when it enters the hole. Also, the diameter of the ball is taken 5.23 mm to produce the same interference fit. The simulation of the cold expansion process is carried out by modeling contact between the face of the hole and the mandrel allowing pressure to be transferred between the contacting surfaces but without them penetrating each other. The thickness is divided to 24 linear brick elements (C3D8R) (Fig. 5). This type of element is adapted in the case of elasto-plastic calculations, and also is well conjugated with contact elements [32].

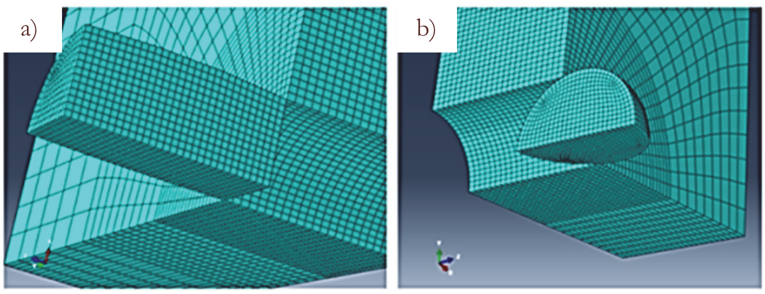


Figure 5: Finite element detail for the assembled model near the hole edge, (a) Expansion with a tapered pin and (b) expansion with a ball.

The material used in this study is an aluminum alloy 7075-T6 for the plate and En 24 grade steel for the pin. The mechanical properties of the plate and the mandrel are given in Tab. 2. According to Mahendra and coworkers [1], the process of the cold expansion is dynamic in nature, leading to large strains in at a relatively small volume element. Moreover, the behavior of the material is nonlinear during expansion. Thus, an isotropic elasto-plastic model with kinematic hardening behavior was used for the plate and elastic behavior for the pin. Kinematic hardening models are provided in Abaqus to model the cyclic loading of metals. The linear kinematic model approximates the hardening behavior with a constant rate of hardening. Isotropic hardening is defined by the yield stress which can be given as a tabular function of plastic strain. The yield stress at a given state is simply interpolated from this table of data, and it remains constant for plastic strains exceeding the last value given as tabular data (Tab. 2).

Mechanical properties	Aluminum alloy 7075-T6	En 24 grade steel
Yong modulus E (GPa)	72	210
Stress yield σ_y (MPa)	500	-
Poisson coefficient ν	0.33	0.3

Table 2: Mechanical properties of aluminum alloy 7075-T6 and En 24 grade steel.

The boundary conditions are presented in Fig. 6. These latter are chosen as reported in [12].

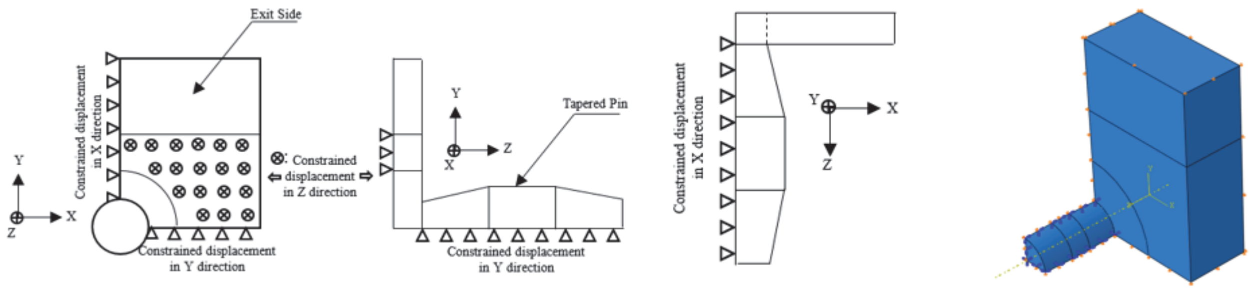


Figure 6: Boundary conditions used in the finite element cold expansion simulation.

So, displacement conditions are imposed on the outer face of the mandrel. This imposed displacement forces the mandrel to penetrate into the hole from one side (Entry) to the other side (Exit). The penetration of the mandrel into the hole causes an expansion of this latter. As a consequence, when the mandrel is removed, the material which is elastically deformed returns back from the expanded state and constrains the material in the elasto-plastic zone to contract. Friction coefficient $\mu = 0.1$ is used taking into account the effect of the friction between contact surfaces during the cold expansion procedure. Practically, this simulates a solid mandrel that is larger than the hole and pulled through the hole using a hydraulic puller. When the larger mandrel slips through the hole, a process of plastic deformation happens and the material around the hole is stressed and strengthened. As a result, the hole has a zone of residual compressive stress around it.

RESULTS

Validation of the model

Before addressing the focused analysis, we first compared our results with those published by Chakherlou and vogwell [12]. These results relate to the expansion with a conical pin L = 3 mm ($\lambda = 7.667$ %).

The residual circumferential stress resulted by cold expansion are presented in Fig. 7. It can be seen that the stress distribution is compressive near the hole but is tensile further from the hole edge. Figs. 7a, 7b and 7c present the actual results compared with those published in [12], for the entrance face, the exit face, and the mid-plane, respectively. From these curves, one can note the correlation between the results, particularly, the extent of the compression zone and the neighboring points to the hole edge. Thus, our model seems relevant, allowing us to approach the analysis of the effect of the mandrel shape on the residual stresses.

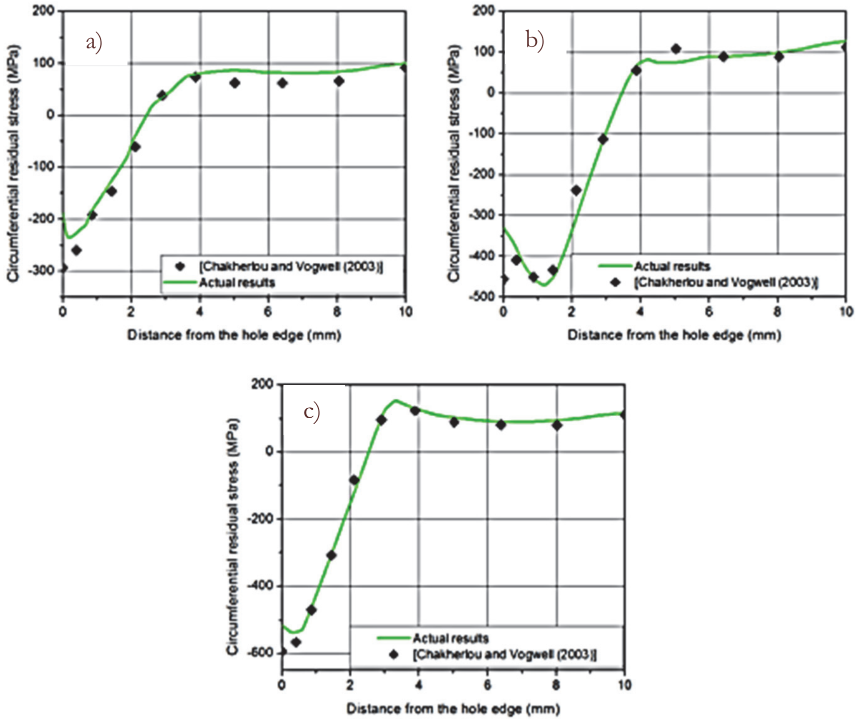


Figure 7: Comparison of the actual results of the residual circumferential stresses along the distance from the hole edge for: a) Entrance face, b) Exit face and c) Mid-thickness plane.

Considering the problematic outlined in this paper, the side that interests us here is the entry of the mandrel. Because, it is established, unanimously that it represents the side where the residual stresses are the lowest, compared to all the hole thickness. Indeed, the results in Fig. 7a (Entrance face) indicates that the circumferential residual stresses at the hole edge are significantly lower than those in Fig. 7b (Exit face) and more lower than those of Fig. 7c (mid-thickness plane). Also, the circumferential stress distribution is not uniform throughout the plate thickness having a maximum compressive value around the mid-plane position and a minimum value at the pin entrance of the hole edge. This last finding agrees well with the literature, thus, the fatigue crack usually initiates from the mandrel entry side. This leads to the weakness of the structure by this side.

This is confirmed by Figs. 8 and 9, where, examples of the residual stresses distribution in the vicinity of the hole edge are given. The iso-values clearly indicate that the residual stresses are no uniformly distributed around the hole and in its vicinity. This is more pronounced in the case of the expansion by the ball where tensile stresses are present in the vicinity of the hole at the entrance face.

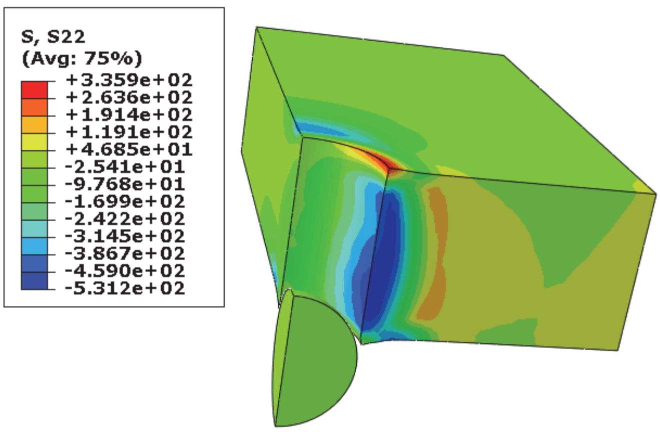


Figure 8: Distribution of the circumferential residual stresses around the expanded hole for the case of the ball mandrel

In contrast, the iso-values of Figs. 9 show a significant improvement in the residual stresses distribution. Indeed, at first, one can note the vanishing of the tensile stresses (positive values) through the hole edge which become compressive stresses (negative values). More even, a decrease of the difference between the induced residual stresses in the entry side and in the exit side of the hole is obtained. The residual stresses in the middle planes remain the higher, compared to the two borders (entrance and exit).

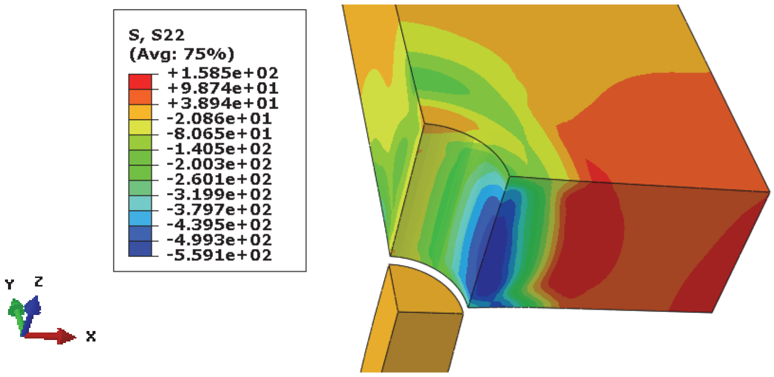


Figure 9: Distribution of the circumferential residual stresses around the expanded hole for the case of the tapered pin mandrel

Subsequently, we present the distribution of residual stresses for the cases studied in this work in order to analyze the effect of the shape of the mandrels used in the cold expansion simulation.

Expansion with a ball

After cold expansion with a ball, tensile stresses were obtained surrounding the entrance and the exit of the expanded hole. Fig. 10 compares the residual stress resulted through the plate thickness. This latter shows that, difference appears at the entrance face. In fact, positive values of the circumferential stresses surrounding the entrance location are present (Fig. 10a). Then, if present, far away the hole edge, the compressive circumferential stresses are insignificant (Fig. 10a). However, the compression zone is significantly reduced, where the residual stresses remain unchanged at the edge of the hole.

Fig. 10d; compare the radial stresses obtained through the plate thickness. Note that lower the tensile radial stresses on the edge of the hole. Indeed, one can observe that the radial stresses are completely compressive (Fig 10b) with a peak compressive value up to -400 MPa in the inlet face.

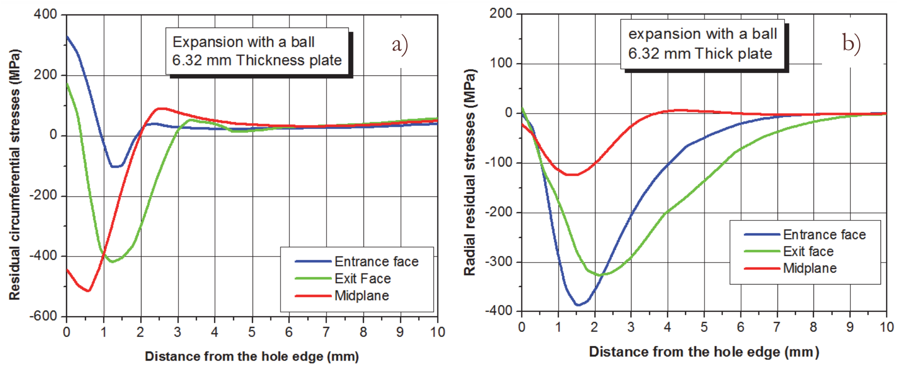


Figure 10: Distribution of the residual stresses trough the thickness for the ball expansion technique: a) circumferential stress, b) radial stress.

Expansion with a tapered pin

In this section, all results are referred to the different taper used in this work as λ=11.5 %, λ =7.667 %, λ =3.883 %, λ =2.775 % and λ =2.3 %.

So, The results obtained using 11.5 % tapered pin model are presented in Figs. 11a and 11b for circumferential and radial residual stresses, respectively. Fig. 11 highlights the effect of the mandrel geometry on the radial and the circumferential stress components compared to the ball mandrel expansion technique. Fig. 14a reveals the presence of tensile stresses at the vicinity of the exit face only. However, The entrance face present low compressive stresses surrounding the hole edge until a distance 2.25 mm, where after, the circumferential stresses become positive (tensile).

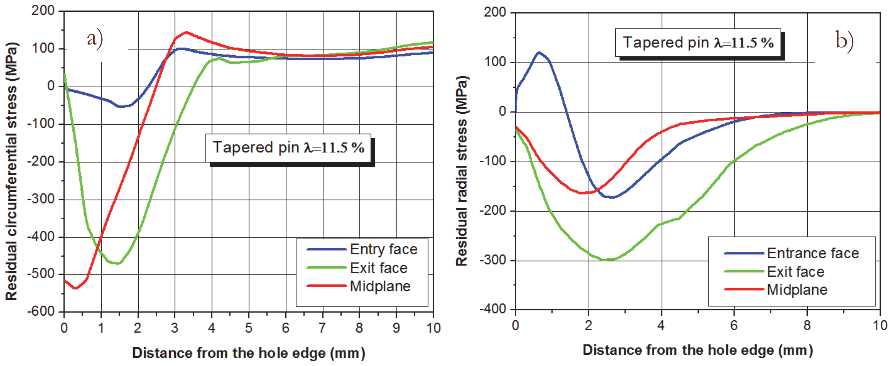


Figure 11: Residual stress distribution vs. the distance from the hole edge to the width border for the case of taper λ=11.5 %: a) circumferential stresses and b) radial stresses.

The radial stress resulting from the 11.5 % taper pin are always tensile near the entrance side of the hole edge, until 1.5 mm. Then, beyond this distance, it reaches the compressive values. After this point, the radial stresses are compressive through all the thickness of the plate (Fig. 11b).
Higher residual compressive circumferential stresses are obtained for the 7.667 % tapered pin in the entrance and the exit face surrounding the hole edge compared to the ball and the 11.5 % taper pin expansion technique (see Fig. 12a). For this case, the maximum values of circumferential stress are always localized around the mid-thickness of the plate through the hole edge until 1mm distance, where the exit face presents the same value as the mid-thickness value. the compressive zone is broader on the side of the mandrel outlet, where it extends up to 3 mm away from the hole edge (see Fig. 12a). Fig. 12b shows the distribution of radial stresses around the hole, in the case of expansion with a conical mandrel of 7.667% taper.

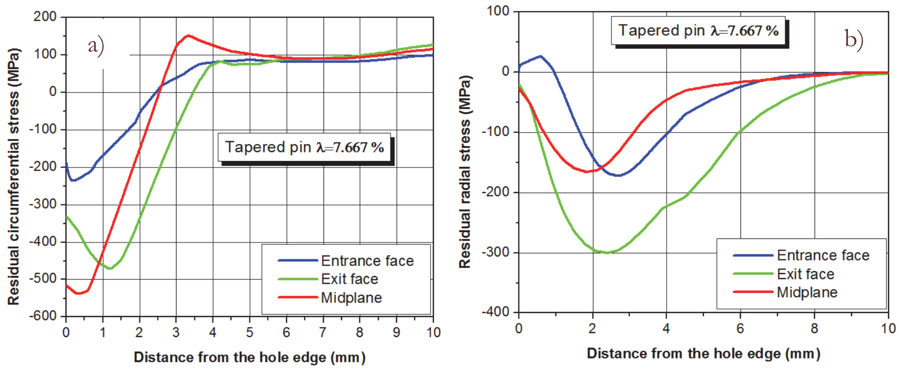


Figure 12: Residual stress distribution vs. the distance from the hole edge to the width border for the case of taper λ=7.667 %: (a) circumferential stresses and (b) radial stresses.

A significant improvement can be noted in the inlet face, where the tensile stresses are reduced to only exist in the vicinity of the hole, but with a lesser peak compared with previous results. This indicates a positive effect of the decrease of the taper. However, the radial stresses in the middle and in the outlet side are not much affected by the taper degree.
Fig. 13a and 13b compares the residual stress distribution through the plate thickness using the 3.833 % taper expansion model. Thus, as shown in Fig. 16a, enhancement appears at the entrance face. In fact, the 3.833 % taper model yields in a higher compressive residual stress for circumferential and radial stress components surrounding the entrance face (Fig. 13a an Fig. 13b).
Fig. 13b indicates an increase of radial compressive stresses obtained at the entrance side location. Effectively, the radial stresses in the entrance face became similar to those surrounding the mid-thickness location. It is noted that, the exit face presents the higher values of compressive radial stress as all the first cases.
For the 2.875 % tapered pin model, similar results are obtained but with lower compressive circumferential stresses surrounding the exit hole edge, as shown in Fig. 14a. While, around the exit side, there is a reduction in circumferential

stress in the hole edge (Fig. 14a). At the time that, the entrance face and the mid-thickness hole location present the same trend as in the case of λ = 3.383%. Fig. 14b shows no change in the distribution of radial residual stresses along the thickness of the expended hole.

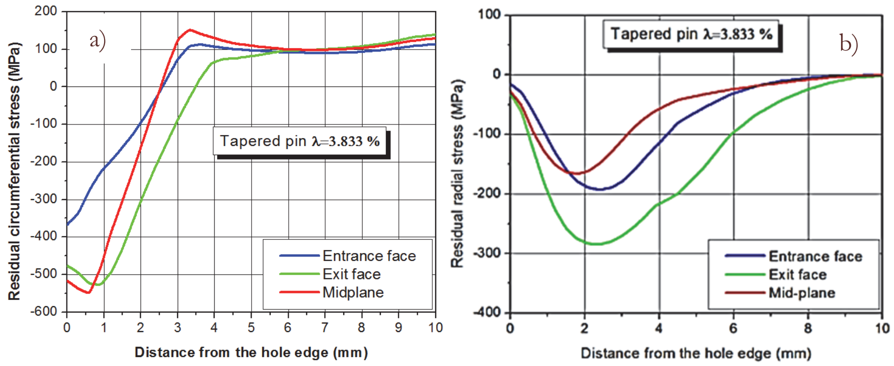


Figure 13: Residual stress distribution vs. the distance from the hole edge to the width border for the case of taper λ=3.883 %: (a) circumferential stresses and (b) radial stresses.

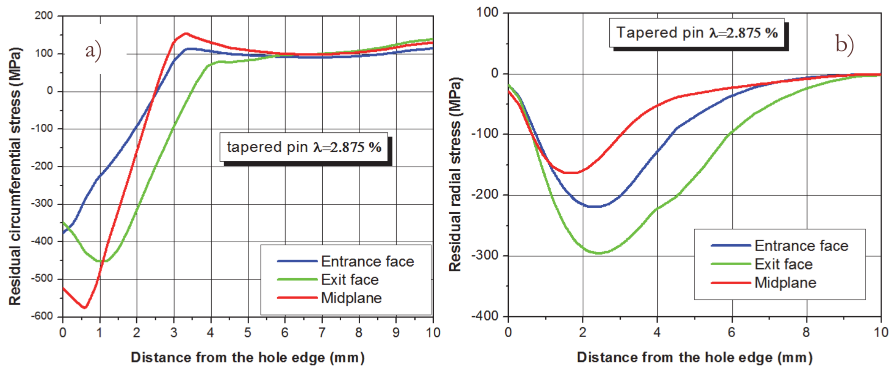


Figure 14: Residual stress distribution vs. the distance from the hole edge to the width border for the case of taper λ=2.875 %: (a) circumferential stresses and (b) radial stresses.

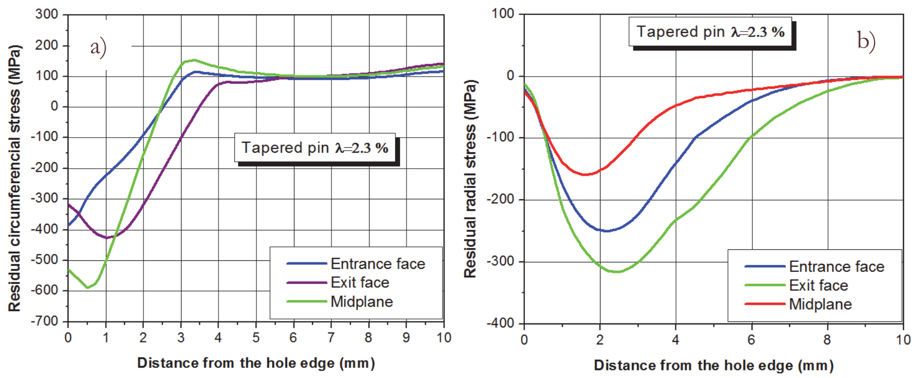


Figure 15: Residual stress distribution vs. the distance from the hole edge to the width border for the case of taper λ=2.3 %: (a) circumferential stresses and (b) radial stresses.

Figs. 15a and 15b illustrate the distribution of circumferential and radial stresses, respectively for the case of 2.3 % taper. One can note similar tendency as resulted in the case of taper=2.875%.

Nevertheless, a slight decrease of compressive circumferential stresses is noted surrounding the exit side of plate (Fig. 15a), indicating that an optimal value for this side is obtained by a taper = 3.833% (Fig. 13a). Furthermore, no change is noted for the radial residual stress through all the hole edge thickness and along the distance from it.

DISCUSSION

The FEM results obtained in this work are in good agreement with the published literature results regarding the distribution of residual stresses around the cold expanded hole. In fact, all models simulated in this work indicate that the circumferential residual stresses are higher around the mid-thickness location of the expanded hole.
To simulate the effect of the mandrel on the distribution of the residual stresses around the hole from the entrance to the exit face, it has been modelized two types of mandrel: a ball mandrel and tapered mandrels defined by different degrees of taper λ.
Figs. 16a, 16b and 16c summarize the results of the circumferential residual stresses distribution for the studied cases, since this latter play a key role in the strength of fastener joints according to the tensile loading direction.
An important result of the present analysis is the fact that, the residual compressive stress, which is responsible for the reduction of the stress concentration at the hole edge, varies along the plate thickness. This effect may be minimized using an adequate tapered pin. Effectively, it is revealed that, the lower taper the higher residual stress are obtained to entrance side (Fig. 16a). Thus, as shown in Fig. 16a and 16b, lower taper λ enhance the residual stress induced by the cold expansion, particularly at the inlet side of the mandrel (Fig. 16a).
Moreover, the degree of taper strongly influences the extent of the compressive zone around the hole edge and far from it. From the moment where, a low taper degree gives better results by matching the circumferential residual stress around the inlet side with those around the exit side of the mandrel.

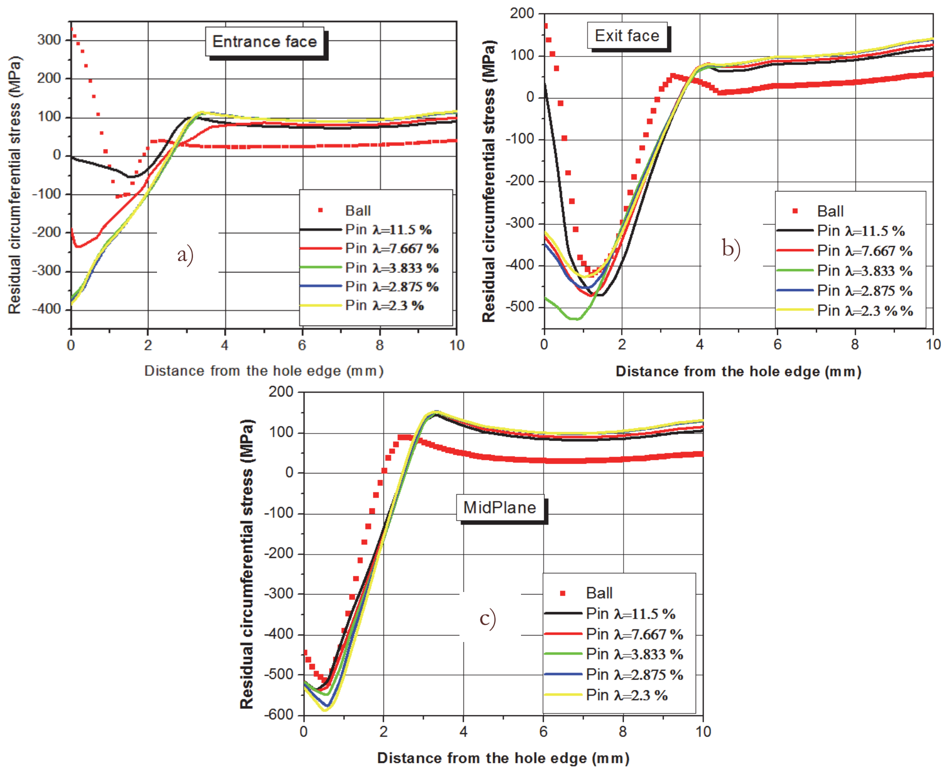


Figure 16: Comparison of the resulted circumferential stresses obtained by different mandrel shapes for: a) Entrance face, b) exit face and c) Mid-thickness plane.

This makes sense, because a substantial taper (λ greater) results in greater gradual axial forces during penetration of the mandrel, as illustrated by Fig. 17. In fact, Fig. 17 clearly indicates the axial force decreases as the taper decreases. This is verified by measuring the force exerted by the mandrel during penetration into the hole. Indeed, it is found that the increment of force applied by the mandrel is greater as the taper is greater (Fig. 17).
This will result in higher pressure on the edge of the hole and thus, significant lateral deformations are generated (in the direction of expansion). Therefore, a low taper allows a graduation of the deformation of the successive layers during the expansion process and facilitates the sliding of the mandrel through the hole, particularly during the penetration of the

conical part of the mandrel. This explains the incontestable effect of the taper on the distribution of residual stresses in the entrance face.

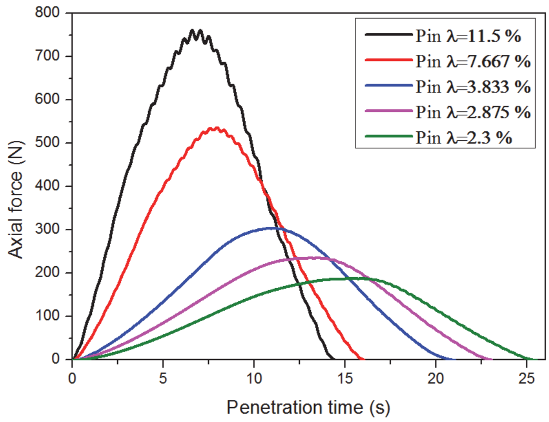


Figure 17: Axial force reaction of the mandrel during penetration through the hole.

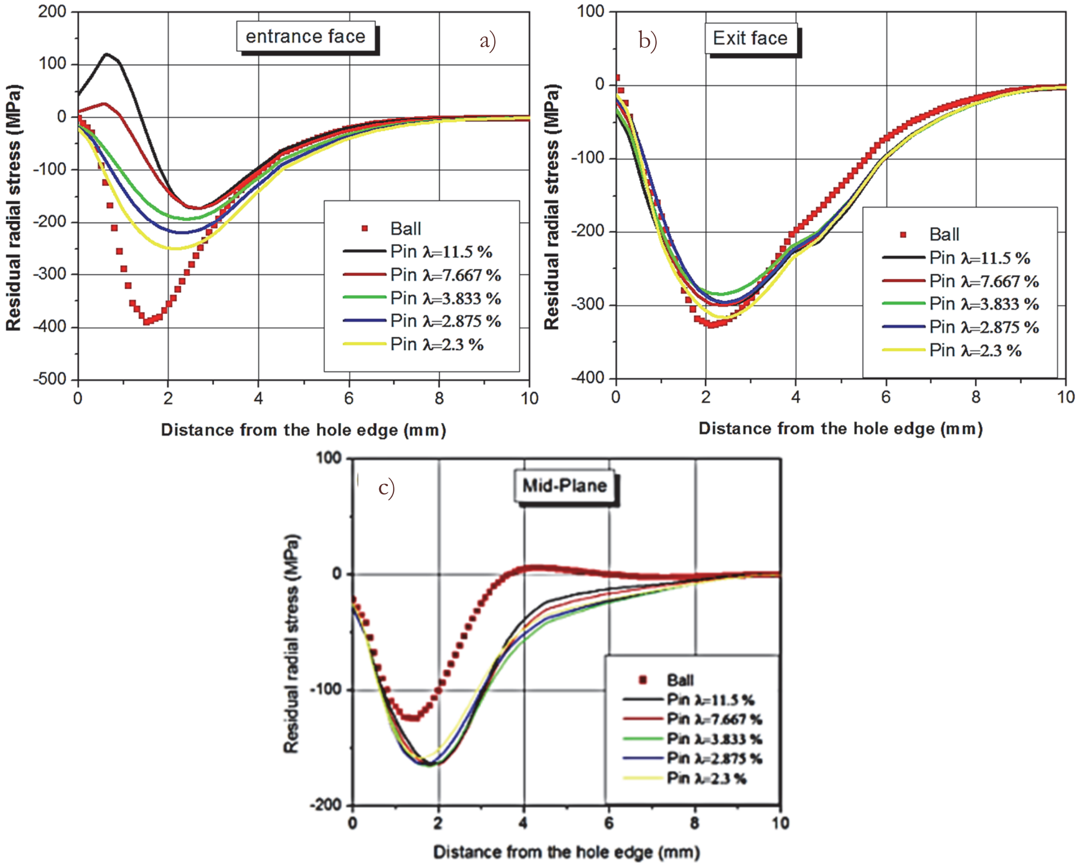


Figure 18: Comparison of the resulted radial stresses obtained by different mandrel shapes for: a) Entrance face, b) exit face and c) Mid-thickness plane.

Since the entrance face presents the lower residual stress, it can be noted that equilibrium between the latter and the exit face is obtained by using a conical mandrel with a taper λ = 2.875 % (see Fig. 14a). The same thing can be said for the outlet side, wherein Fig. 16b shows an improvement of residual stresses as a function of the taper. Much more, a taper of 3.833% optimizes the circumferential residual stresses.

Regarding the radial residual stresses, the same finding is raised to the inlet face. Fig. 18a shows the effect of the mandrel shape on the radial residual stresses distribution surrounding the entrance face. It is evident in this figure that lower degree

of taper increases the compressive radial stresses. Since, one can note a tensile stresses near the hole edge induced by the passage of the conical mandrel with taper λ = 11.5% and less with λ = 7.667%. For the exit face, the effect of the mandrel is not obvious, so the effect is not considerable (Fig. 18b).
At the mid-thickness of the hole, the radial stresses have similar distribution trends for any taper, except for the case of the ball mandrel, where the compressive radial stresses are lower (Fig. 18 c).
Fig. 19 illustrates the distribution of the circumferential residual stress along the thickness of the hole, for the two types of mandrels and for different tapered pins λ. All comments discussed above are clearly identified in this figure. So, one can note that the expansion with a ball mandrel in a thick plate leads positive stresses on the vicinity of both sides of the hole (the inlet and the outlet). However, residual stresses in mid-thickness of the hole are relatively compressive. Better yet, Fig. 19 shows that the circumferential residual stresses along the thickness are slightly uniformly distributed for lower taper. This confirms the hypothesis of the severity of the high taper on the lateral deformations of the material around the hole.

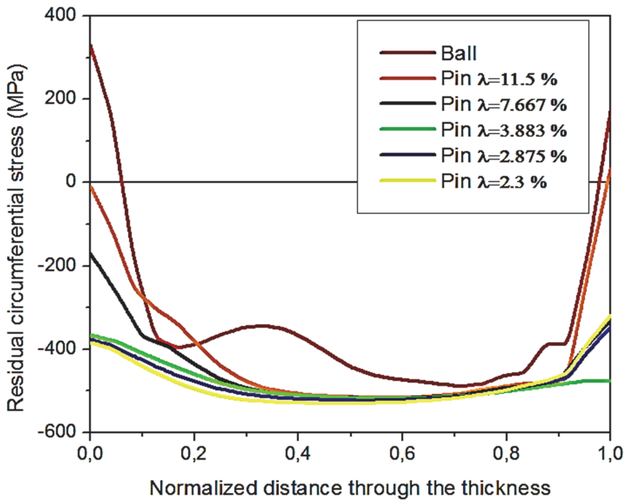


Figure 19: Comparison of Distribution of the circumferential residual stresses along the thickness for different mandrel shapes

The FEM simulation yielded the results that, with lower taper, as 3.83%, 2.875 % and 2.3 %, a significant gain in circumferential residual stresses is obtained.

CONCLUSION

A numerical analysis of residual stress distribution around a cold expanded hole was conducted in this work. Special attention was made on the mandrel shape used for the expansion procedure. Thus, common types of mandrels were modeled, such as the ball and the conical mandrel. For the latter, it was varied its taper degree defined by the relation (2). According to the length of the conical part, the degrees of taper used are: 11.5%, 6.667%, 3.833%, 2.875% and 2.3%. So, a study of the effect of the geometric shape for the same type of tool is described here including a distribution of residual stresses along the plate thickness is also discussed.
Following the studied cases, the obtained results allow us to make the following conclusions:

- The residual stresses around the expanded hole are not uniformly distributed. And this regardless the type of the oversized tool used for the expansion,
- The cold expansion with a ball results in tensile residual stresses around the hole edge.
- In any way, the ball mandrel technique is unsuitable for thicker plates. However, it remains useful in the case where the load direction coincides with the radial direction.
- The tapered pin is more suitable for the cold expansion, especially for thick plates.
- The residual stresses distribution along the hole thickness can be broadly optimized, by using appropriate geometry of the mandrel. In fact, low taper degree is more suitable than the high taper degree.
- Taper degrees lower than 7.667% leads to higher values of compressive circumferential stresses around the entrance face of the hole edge. Especially, taper of 3.83 % is recommended.

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