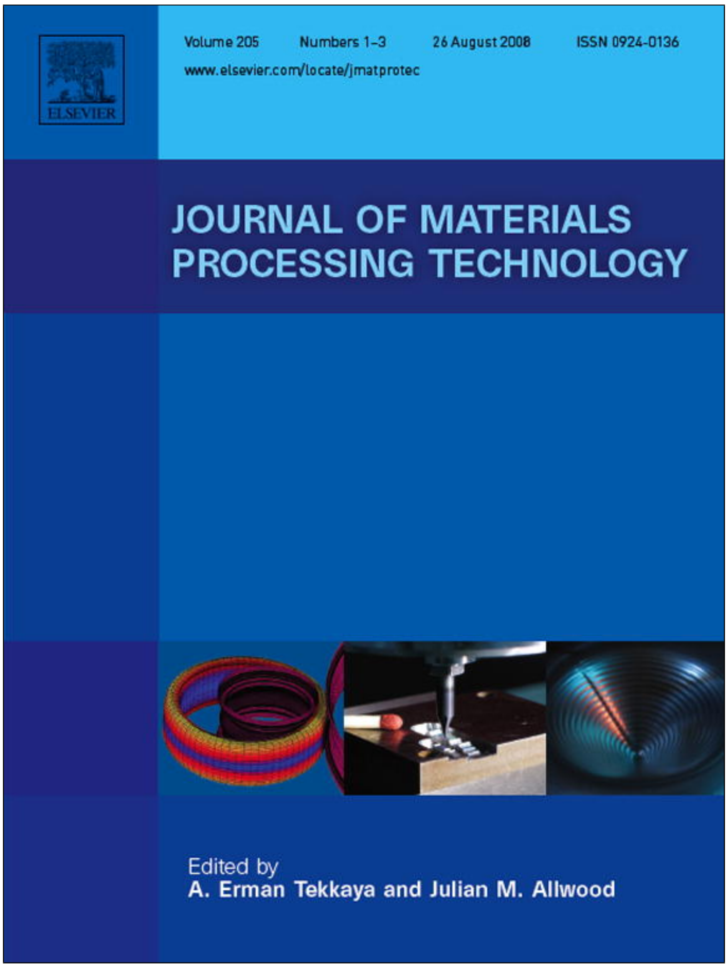
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Finite-element simulation of residual stress induced by split-sleeve cold-expansion process of holes

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ABSTRACT

A three-dimensional finite-element simulation was conducted for a split-sleeve cold-expansion process in order to determine the residual stress field around an expanded hole. The commercial FEA software DEFORM-3D™, a Lagrangian implicit code designed for metal forming processes, was used to model the cold-expansion process of a fastener hole. The results show a through-thickness residual stress field in good agreement with the analytical solution developed by Guo. Moreover, the simulation has highlighted the effect of the split sleeve and the plate thickness on the residual stress field.

1. Introduction

Fatigue cracks originate from stress concentration such as that produced by a fastener hole subjected to a cyclic load. Therefore, several companies have developed various techniques to reduce the effect of the stress concentration around fastener holes. A cold-worked process is widely used to generate beneficial residual stresses into an annular region around the hole. This technique inhibits the propagation of a fatigue crack; therefore, an accurate simulation of the cold-expansion process for a hole is necessary if the residual stress is to be used to assess fatigue life.

The cold-expansion, which is developed by the *Fatigue Technology Inc.* (FTI, 1994), is obtained by using increased pressure to plasticize an annular zone around the hole (Fig. 1). The pressure on the surrounding material is realized by interference generated between the drilled plate and the pressuring element, i.e. the mandrel. Such interference causes a stress state which decreases with increasing distance from the edge of the hole. When the mandrel is removed and the superficial pressure on the hole is erased, a residual stress field is created due to the action of the elastic deformed material on that under plastic condition. A split sleeve is introduced to reduce the shear of the material surrounding the hole and to ensure radial pressure on the plate; however, the opening of the split in the sleeve distributes hoop residual stresses asymmetrically.

In the past, analytical models, experimental techniques, and numerical simulations have been developed to predict the residual stress field induced by a cold-expansion process of a hole. Analytical studies have determined the closed-form solution of the residual stress for considering the material's yield limit on unloading step (Guo, 1993; Nadai, 1943; Hsu and Forman, 1975; Rich and Impellizzeri, 1977). However, many solutions are based on two-dimensional approximations, and theories are not able to predict the through-thickness residual stress field. Therefore, these solutions would predict fatigue life non-conservatively. The residual stress can be measured by either non-destructive or destructive methods. The non-

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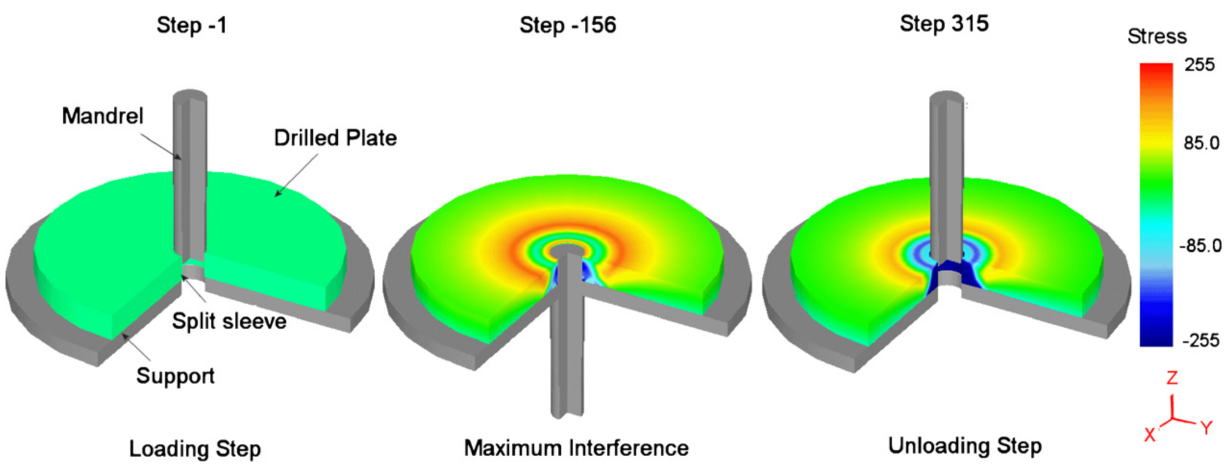

Fig. 1 – Sketch of cold-expansion process of a hole showing the hoop residual stress at 4% nominal interference.

destructive X-rays (Dietrich and Potter, 1977; Priest et al., 1995; Stefanescu et al., 2002) and neutron diffraction techniques (Stacey et al., 1985) are widely used, but their result must be adequate with respect to low in-depth resolution. Moreover, non-destructive methods cannot precisely predict reverse-yielding behavior. The destructive Sach's boring-out technique (Garcia-Granada et al., 2001) does not consider the non-uniformity and complexity of residual stresses through the thickness of the plate; it estimates the average of through-thickness residual stress. Previous researches (Pavier et al., 1985, 1998; de Matos et al., 2005) have concentrated mainly on modeling the residual stress field using numerical two-dimensional or three-dimensional methods; nevertheless, these finite-element (FE) analyses take advantage of the symmetry of the drilled plate in order to model only a fourth of the model. Consequently, these analyses neglect the effect of the opening of the split in the sleeve.

This paper presents a simulation of the entire split-sleeve cold-expansion process of a hole considering all steps and process parameters and using the DEFORM-3D^{TM} (Fluhrer, 2003) code designed for metal forming processes. This realistic process simulation reveals the residual stress field around an expanded hole of a 5083-H321 aluminum plate at 4% nominal interference; thus, the result is compared with the analytical model developed by Guo (1993). The residual stress field has been found to change through the thickness. Also, the effect of the plate thickness on the hoop residual stress is investigated by means of a parametrical analysis. Finally, the effect of the position of the opening of the split in the sleeve is also examined.

2. Finite-element simulation

The 3D numerical analyses were carried out simulating the cold-expansion behavior of a 5083-H321 aluminum plate at 4% nominal interference, *I*. Rich and Impellizzeri (1977) and Pavier et al. (1998) had shown that the best mechanical properties are obtained for this value of nominal interference. All objects of the cold-expansion process were simulated for this research, Fig. 2. The split sleeve, the support, and the mandrel have better mechanical properties than the plate has; consequently, the split sleeve was considered elastic, while the mandrel and the support were assumed to be rigid bodies. The material behavior of the plate was considered with an elasto-plastic model. The elastic data were introduced by adding the Young's modulus ($E = 68{,}900$ MPa) and Poisson's ratio ($\nu = 0.3$) of the 5083-H321 aluminum alloy in DEFORM-3D^{TM} interface. In plastic domain, the plastic-flow behavior obeys to a non-linear stress–strain curve, Eq. (1):

$$\sigma = C\varepsilon^n \qquad (1)$$

where σ is the flow stress, ε the strain, C the strength coefficient, and n is the strain-hardening exponent.

The ASTM E 646-00 standard test method (ASTM, 2000) was used to calculate the power curve parameters. A set of tensile specimens was used to determine the C and n parameters. Thus, the parameters were directly introduced in DEFORM-3D^{TM} software to depict the material behavior of the plate.

A kinematic hardening model, which uses Bauschinger's parameter (Bauschinger, 1881), $\beta = 1$, was assumed in this study.

The elastic data of split sleeve were introduced to depict the material behavior. In particular a Young's modulus of 210,000 MPa and a Poisson's ratio of 0.3 were adopted in this simulation.

The shape of the plate was assumed as a circular disk with a 2.9 mm radius hole, r_a; the outer radius, r_f, was 25 mm. Previous research has revealed that the exact dimension for the outer radius did not affect the results near the hole edge provided that the outer radius was large enough (Guo, 1993). The plate thickness, s, was 5 mm, a typical value used in practical structures.

Tetra elements with four nodes were used for the mesh of the plate and the split sleeve (Fig. 2). The element size was improved through a finer mesh density corresponding to the hole edge in order to predict the steep stress gradient that arises there. The plate contained 33,000 elements and

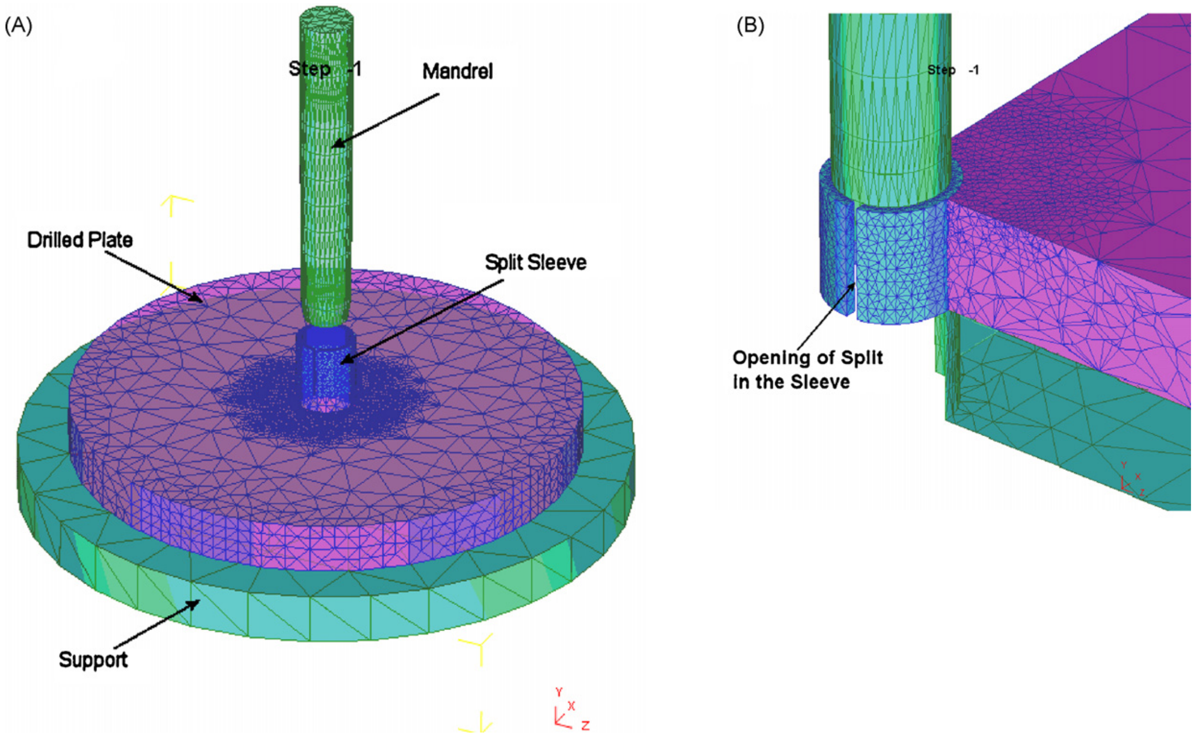

Fig. 2 – FE model used to simulate the cold-expansion process of the hole: (A) complete model and (B) detailed view close to hole edge.

the split sleeve contained 20,000; these numbers were sufficient to ensure convergence. During the mandrel movement, the remeshing was automatically calculated in order to conveniently handle the remeshing of objects undergoing large plastic deformation. The shape of the support was a drilled disk, which avoids the axial displacement of the plate due to the mandrel's movement during the process.

Boundary conditions for an incremental, interactive simulation specify how the boundary of an object interacts with other objects and with the environment. The boundary contact conditions among objects (mandrel, split sleeve, plate, and support) were expressed by means of contact elements. During the process, the contact elements are automatically drawn. The mandrel speed, v, was 4 mm/min. The coefficient of friction, μ, was assumed to be equal to 0.3, a typical value representing the contact between aluminum and steel. The loading and unloading were simulated through a total of 315 steps with mandrel increments equal to 0.2 mm.

Table 1 shows the main parameters of the plate and the mandrel which were used to model the cold expanded hole in this research.

3. Results and discussion

3.1. *Load prediction*

The load necessary to pull down the mandrel during the cold-expansion process was predicted by the numerical analysis. An experimental test (Pasta, 2007; Nigrelli et al., 2004) was performed to the same process conditions considered in the numerical simulation; the dimension and geometry of the objects are similar to those mentioned in Section 2. The load and stroke data were recorded for several steps during the cold-expansion process. Thus, the numerical load versus stroke curve was compared to an experimental test carried out on the same 5083-H321 aluminum alloy, Fig. 3.

Fig. 3 shows how the load magnitude gradually rises up to a maximum as the interference increases to high values. The maximum value of the load corresponds to maximum interference between mandrel and plate. Thus, the load decreases until to zero because the taper mandrel come back to initial position. Although the analytical curve does not exactly fol-

Table 1 – Process parameters used for the numerical simulation

Material model	Material parameters (referred to Eq. (1))		Geometry	Boundary conditions
Plate				
Elasto-plastic	$n = 6.93$, $C = 400$	$\beta = 1$, $\sigma_y = 255$ MPa	$r_a = 2.9$ mm, $r_f = 25$ mm, $s = 5$ mm	Contact with split sleeve and support
Mandrel				
Rigid	Taper 1:100		$I = 4\%$	Contact with split sleeve $v = 4$ mm/min $\mu = 0.3$

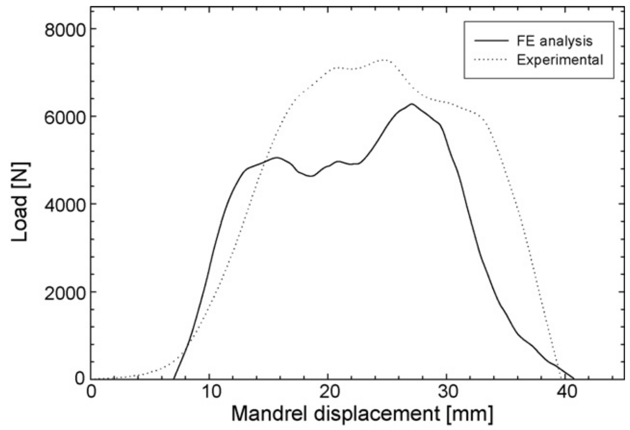

Fig. 3 – Comparison between the experimental test (Pasta, 2007; Nigrelli et al., 2004) and FE predictions of load vs. stroke (displacement) of mandrel.

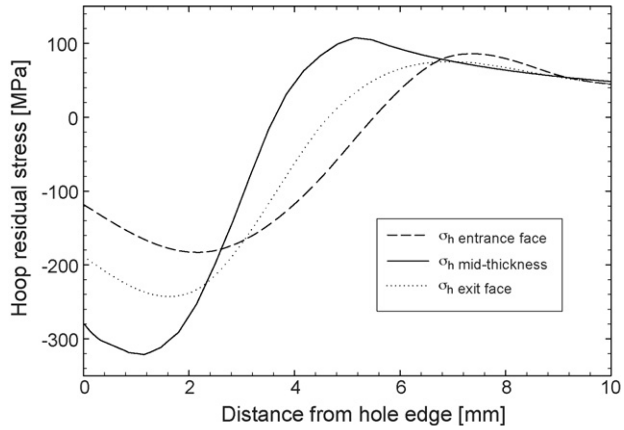

Fig. 4 – FE determination of hoop residual stress at different through-thickness positions: entrance face, mid-thickness, and exit face. The plate is 5 mm thick.

low the shape of the experimental curve; Fig. 3 shows that the maximum value of the load is calculated with reasonable accuracy. The numerical determination of the maximum load could be used to design the puller machine of the cold-expansion process for holes.

3.2. *Residual stress distribution*

The cold-expansion simulation shows the hoop stress evolution around the hole during the loading and unloading steps. During the loading step, the magnitude of the compressive residual stress is achieved with few steps, and the gradual pressure of the mandrel improves the plastic radius up to a maximum value obtained at the maximum nominal interference. During the unloading step, the elastic–plastic release of the plate generates the reverse-yielding zone.

Only the results for the hoop residual stress are presented, because this component of stress is the most influential component in fatigue crack growth (Pasta, 2007; Lacarac et al., 2000; Wang and Zhang, 2003). The results are initially presented in a direction of 90° to the split in the sleeve.

Fig. 4 shows the FE prediction of hoop residual stresses through the thickness of the plate from the entrance face to the exit face.

The magnitude of compressive hoop residual stresses on the entrance and the exit faces are lower than the stresses on the mid-thickness. This zone of low residual stress could initiate an early fatigue crack comparable to the crack growth in a plain hole (Lacarac et al., 2000). Low hoop residual stresses on entrance and exit faces may be caused by the shear stress from the axial movement of the mandrel. The compressive residual stresses into the annular region around the hole reduce the origin of cracks. During fatigue testing, this residual stresses act to change the effective stress intensity factor at the crack tip, i.e. the crack growth rates are lower than those in absence of residual stress. The residual stress profiles are in agreement with other studies presented in previous literature (Pavier et al., 1985, 1998; de Matos et al., 2005).

3.3. *Comparison with analytical theory*

Working on residual stress distribution, Guo (1993) achieved the exact solution for a cold-worked hole considering Ball's model (Ball, 1995) for a non-linear response of the unloading step. This analytical solution, such as all other analytical models (Nadai, 1943; Hsu and Forman, 1975; Rich and Impellizzeri, 1977), does not provide the stress differences through the thickness. Guo's model, which is rather complex (Guo, 1993), represents fine the real residual stress distribution at mid-thickness without considering the split of the sleeve. Therefore, the mid-thickness residual stress of FE analysis is compared with Guo's solution (Fig. 5).

Fig. 5 shows a good agreement between the numerical simulation and the analytical model. In particular, the FE prediction slightly overestimates the maximum and minimum magnitudes of hoop residual stress. However, the plastic radiuses of the plastic and the elastic–plastic boundaries are in good agreement with the values of Guo's solution. Such a result demonstrates that DEFORM-3D^{TM} is able to predict the residual stress of the split-sleeve cold-expansion process.

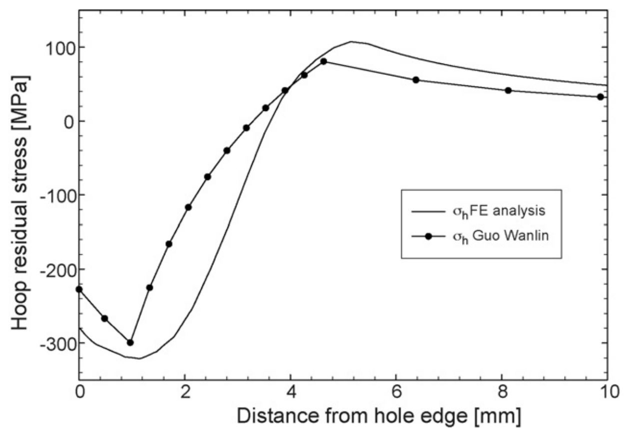

Fig. 5 – Comparison of FE mid-thickness hoop residual stress with Guo's solution.

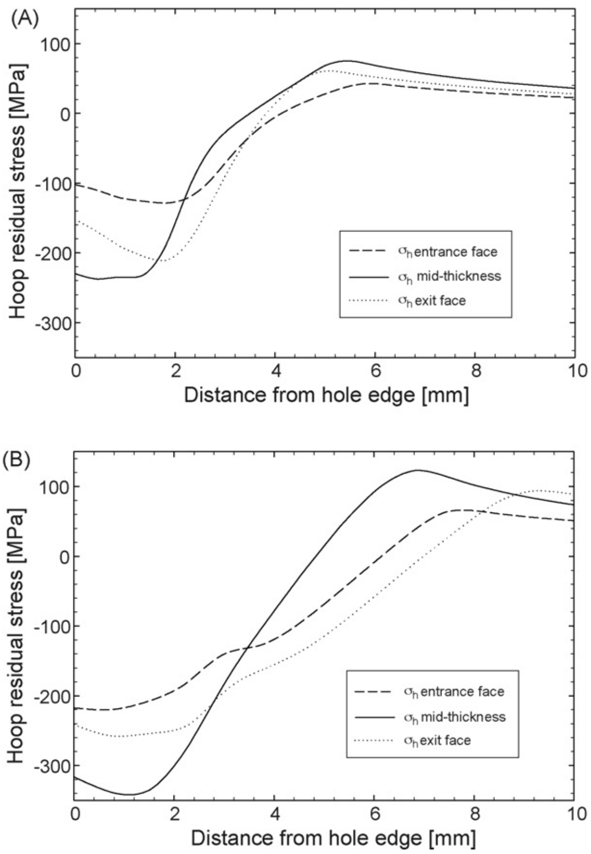

Fig. 6 – Hoop residual stress distribution at different through-thickness positions: (A) plate 3 mm thick and (B) 10 mm thick.

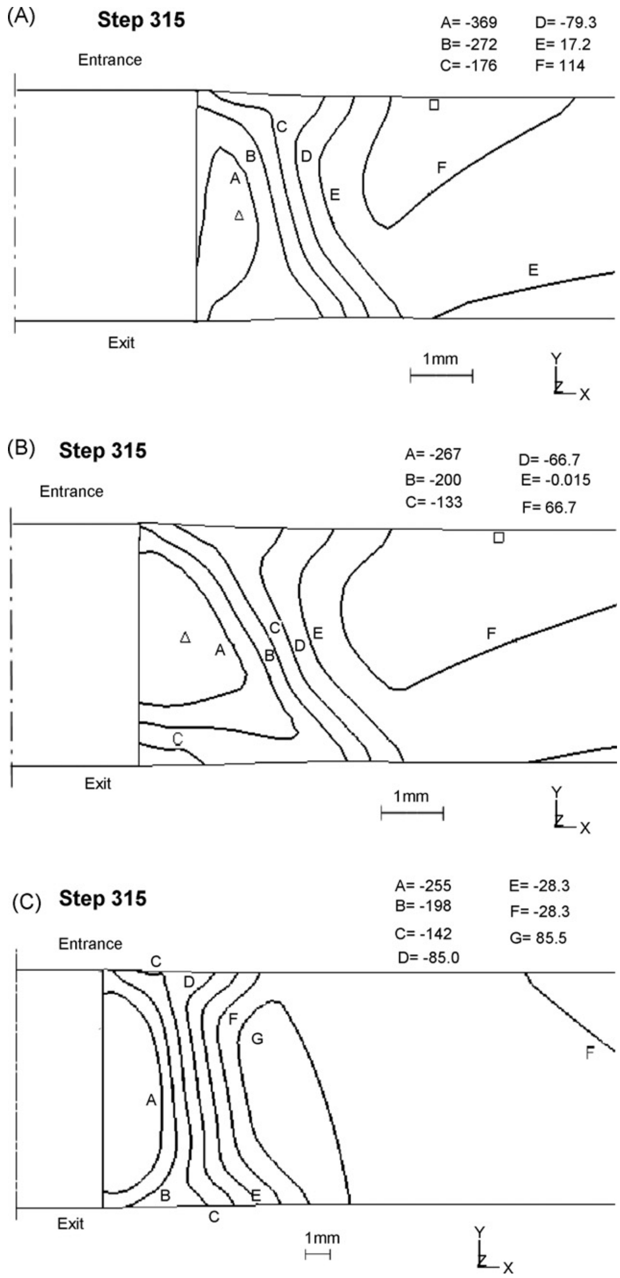

Fig. 7 – Residual stress maps of the drilled plate for (A) 3 mm thick, (B) 5 mm thick, and (C) 10 mm thick.

3.4. *Effect of the plate thickness*

It is noticed in Ozdemir and Hermann (1999) that the change in plate thickness can determine a different distribution of the residual stress. Therefore, this effect has been investigated by evaluating the residual stress field around the cold-worked hole for three values of plate thickness. Thus, the results are compared to clarify the effect on the residual stresses of the ratio between the thickness and hole diameter.

The FE analyses were carried out for 3 mm, 5 mm, and 10 mm plate thicknesses considering a constant hole diameter, $d_a = 5.8$ mm. These thicknesses are in agree with the available values in the FTI's specification. The hole diameter and thickness can be modified during the design stage. The mandrel geometry and the mechanical properties of plates were considered the same of the numerical analysis described in Section 2.

Figs. 4 and 6 show, respectively, the hoop residual stress profiles for 5 mm plate thickness and for 3 mm and 10 mm thickness. Fig. 7 shows the residual stress maps of the half cross-section of the plate for 3 mm, 5 mm, and 10 mm thickness.

It can be noticed that the hoop residual stresses increase as the plate thickness increases from 3 mm to 10 mm and this enhancement is more remarkable for thickness ranging from 3 mm to 5 mm, Figs. 4 and 6(A). Moreover, the enhancement in plate thickness determines higher values of the plastic radius, Fig. 6(A) and (B). In fact, the plastic radius rises from 5 mm to 6.5 mm approximately. It can be seen for 10 mm plate thickness that the compressive residual stresses on the entrance face are close to those at exit face and that the mid-thickness stresses are slightly higher, Fig. 6(B). In this way, a homogeneous distribution of residual stress is obtained for 10 mm plate thickness, Fig. 7(C).

Therefore, an optimal value of ratio between the plate thickness, s, and hole diameter, d_a, can be utilized. In this study, in particular, it has been found that the compressive residual stress significantly improves approximately until to

$s/d_a = 1$ ratio. Then, higher ratios contribute to provide uniform residual stresses distributed through the thickness.

3.5. *Effect of the split sleeve*

FTI's process (FTI, 1994) specifies the use of the split sleeve to avoid material tearing and to protect the hole from strong friction caused by high interference. Nevertheless, this object causes a non-symmetric stress distribution because of the lack of pressure on the plate at the opening of the split sleeve. Consequently, low hoop residual stresses occur in the opening zone. This zone of low stresses is called the pip location.

Fig. 8 shows the non-symmetric distribution of displacement, influencing the residual stress field. Because of this, the hoop residual stress distribution should be analyzed for different angular directions relative to pip location. This study was performed for three different angular directions, 0°, 90°, and 180° relative to pip location. The hoop residual stress distributions will be presented for the mid-thickness.

Figs. 9 and 10 show the contour lines and the profiles of hoop residual stresses, respectively, for the investigated angular directions.

Fig. 9(A) displays a symmetric residual stress distribution around a cold-worked hole configured at 90°. The residual stress map changes remarkably at the pip location (Fig. 9(B)). In fact, the highest contour line shows low hoop residual stresses close to the hole edge.

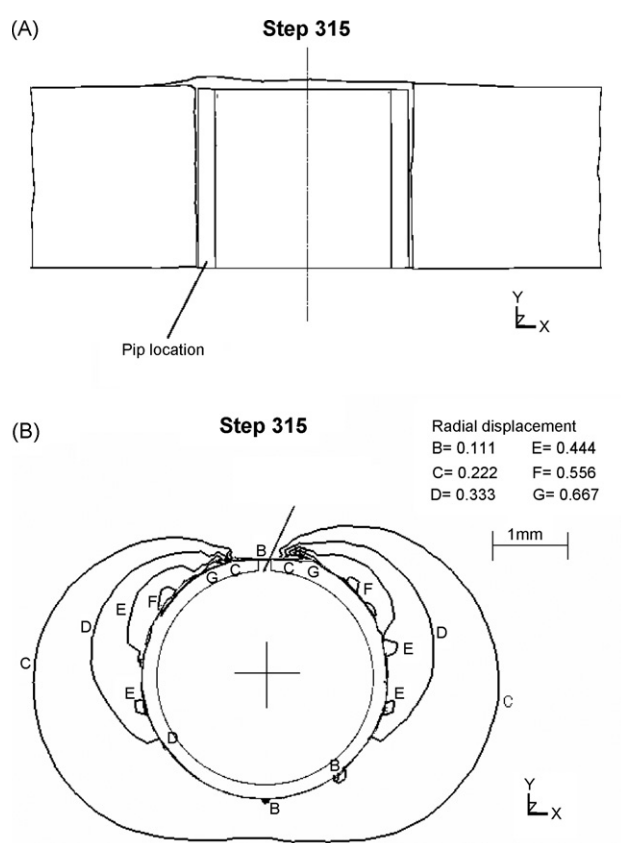

Fig. 8 – (A) Deformed shape and (B) map of radial displacement of the cold expanded plate showing the influence of the opening of the split sleeve.

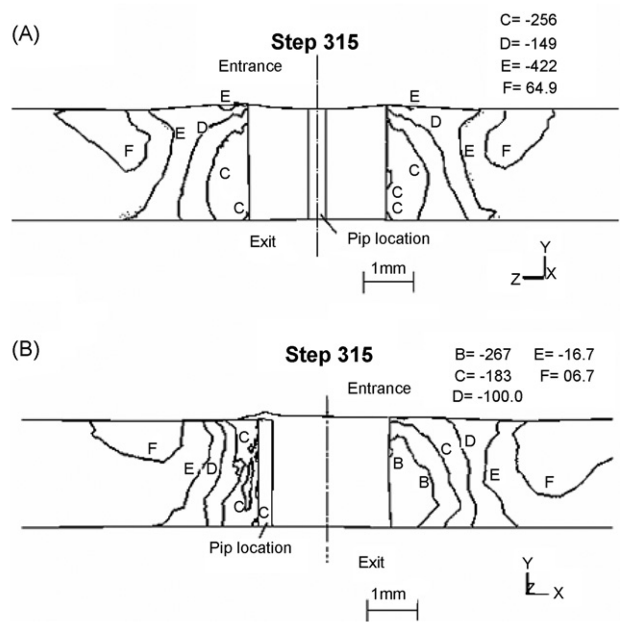

Fig. 9 – Maps of the hoop residual stresses at 0°, 90°, and 180° relative to pip location: (A) 90° configuration and (B) 0° and 180° configurations.

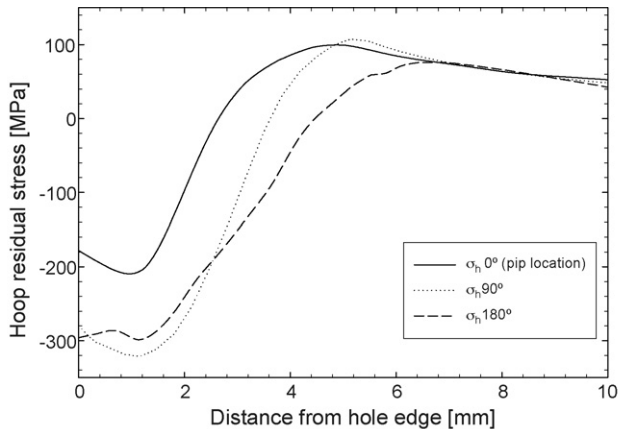

Fig. 10 – Hoop residual stress profiles for mid-thickness at 0°, 90°, and 180° relative to pip location.

As reflected in Fig. 10, the hoop residual stresses at pip location are reduced by approximately 34% and these low values could determine early fatigue crack propagation comparable to the crack growth in a plain hole. The 180° angular direction shows stresses slightly lower than to those at the 90° angular direction. Indeed, it can be seen that the magnitude of the hoop residual stress is low at the plastic radius of the reverse yielding. The higher values of hoop residual stresses are achieved at 90° angular direction.

4. Conclusions

A three-dimensional FE simulation of the split-sleeve cold-expansion process was carried out simulating the cold-expansion behavior of a 5083-H321 aluminum alloy and using the DEFORM-3D^{TM} code designed for metal forming processes. The realistic process simulation, which was performed at 4% nominal interference, indicates that the hoop residual stresses were compressive with values decreasing from the exit to entrance faces. The residual stress results on the mid-thickness were compared with the analytical solution developed by Guo, and the good agreement between the numerical and analytical models demonstrates that the DEFORM-3D™ code can predict the residual stress of the cold-expansion process. In addition, the magnitude of load pulling down the mandrel is close to experimental one at highest interference; this result could be used to design the puller machine of the cold-expansion process for holes. The effect on the residual stresses of change in plate thickness was also investigated. The analyses show that the compressive residual stresses improve as the plate thickness increases. Moreover, it has been shown that higher plate thicknesses provide distributed compressive hoop residual stresses through the thickness. Finally, the opening of the split in the sleeve influences the hoop residual stresses, which are lower at the pip location. This low residual stress distribution would be expected to initiate early fatigue crack propagation by reducing the beneficial effect induced by cold working process.

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