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3-d axisymmetric numerical analysis and experimental study of the fastener hole coldworking process

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ABSTRACT

Most theories developed for the determination of the residual stresses and strains near the edge of a coldworked hole have been based on two-dimensional analysis considerations. They do not reflect faithfully the actual situation because of the three-dimensional nature of the coldworking procedure.

In the present work, the ABAQUS finite element computer program was used to simulate the three dimensional behaviour of a cold expanded fastener hole. The through thickness hole profile and the variation in residual stresses and strains on both lateral surfaces and in the centre of the plate are studied and compared with experimental measurements of the residual stresses on both surfaces together with the values obtained from theoretical models proposed in the literature.

Since the present analysis takes into account the non-uniformity of the coldworking procedure through the thickness of the hole, the proposed model may effectively be used to study the effect of the coldworking parameters on the residual stress distribution and thereby on fatigue life.

INTRODUCTION

Fastener holes have always been a source of concern in the aeronautical industry. Being stress concentrators, they have a strong influence on the fatigue life of a component since they promote the initiation and propagation of cracks that ultimately lead to failure. In order to improve the fatigue life of components with fastener holes, innovative methods that are simple, relatively low cost and that do not add weight or material to the component have been developed [1].

Among several processes suggested for improving the fatigue life of fastener holes, coldworking is a method that generated much interest during the 1970's. The idea behind coldworking is to induce highly compressive residual tangential

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stress distributions at the hole edge that act against the tensile stress generated by the remote loading. The coldworking of fastener holes by mechanical means was found to be a simple cost effective way to improve fatigue life by a factor of two to fourteen [2-4]. Unfortunately, the influence of the different parameters of the process was not well studied and the beneficial effect of coldworking was never integrated in the design against fatigue failure for commercial aircrafts. Today, the interest in coldworking is rekindled as aircraft manufacturers seek better fatigue resistant components in their new aircrafts as well as extended design lives from the maintenance of their aging fleet.

In order to thoroughly comprehend the beneficial effect of coldworking fastener holes, the three-dimensional response of the material subjected to the coldworking procedure must be studied [5]. In this work, a three-dimensional axisymmetric finite element model is examined to evaluate the distribution of the stresses and strains through the thickness of the coldworked component. The hole profile after coldworking and the plastic zone size through the thickness are also determined. The results are then compared with the experimental data and theoretical values obtained from two typical approaches proposed in the literature.

EXPERIMENTAL PROCEDURE

The coldworked specimens were made from a 6.35 mm (1/4") thick plate of 7475-T7351 aluminum. The material used has a yield strength of 414 MPa (60 x 10^3 psi), a modulus of elasticity of 68.9 GPa (10 x 10^6 psi) and a Poisson's ratio of 0.31.

The central hole of the specimens was cold expanded using the Boeing split sleeve coldworking procedure. In this procedure, a mandrel is pulled through a lubricated split sleeve inserted into the fastener hole, thereby plastically deforming the material and inducing residual stresses around the hole edge. The original hole diameter in the specimens was 6.01 mm (0.2366") and a cold expansion level of 4% was considered. After cold expanding, reaming was performed on the hole and its final diameter was 6.35 mm (0.25").

The residual tangential stresses were then measured using the CANMET portable X-ray diffractometer [6]. The diffractometer had position sensitive detectors and used the multi-exposure technique to evaluate the stress values. The measurements were taken from the edge of the hole outward radially on both sides of the specimen. Because of the low intensity of X-rays reflected from the aluminium material, a relatively large area of 1.6 mm x 3.2 mm (0.063" x 0.126") on the specimen surface was subjected to the X-rays at one time. Thus the X-ray diffraction technique gives only the average stress level over the area covered by the X-rays. To minimise this effect, overlapping areas were chosen in the vicinity of the hole edge where the gradient of the tangential stress is the most significant. On average, ten measurements were performed and the distance between two subsequent measurements was gradually increased farther from the hole edge.

FINITE ELEMENT ANALYSIS

The numerical model was generated to represent as faithfully as possible the coldworking procedure applied to the Al 7475-T7351 specimens. The finite element model shown in figure 1 represents the mandrel during the coldworking process of a specimen hole.

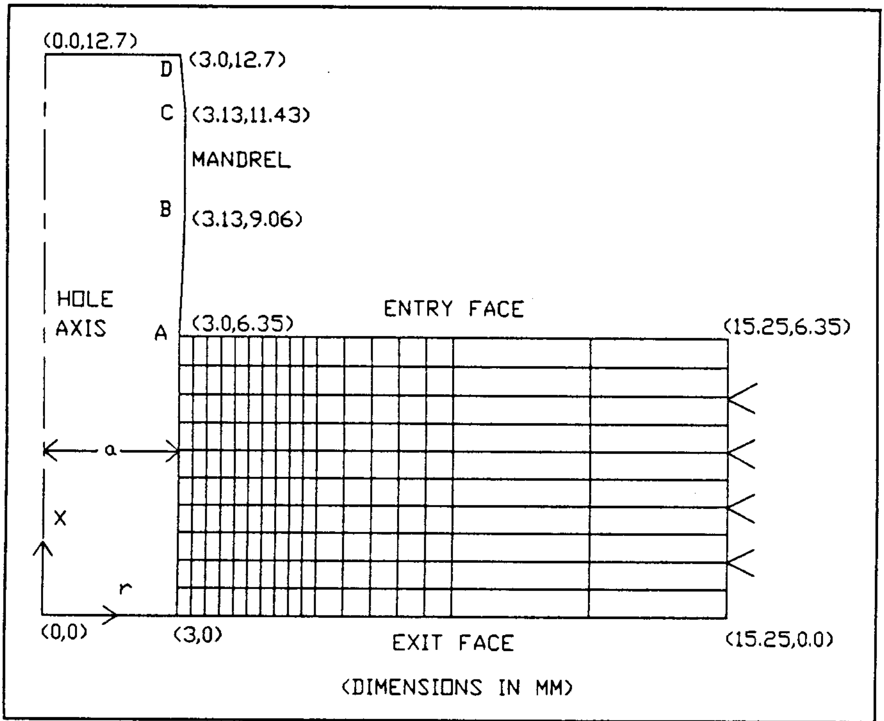

Figure 1: Numerical finite element model of a fastener hole about to be coldworked

Because of the axisymmetric nature of the process only one half of the total section of the specimen is modelled. The model is made of one hundred and seventy three-dimensional axisymmetric elements that allow for bi-quadratic displacement of the eight nodes. The smallest element is 0.64 mm x 0.31 mm (0.025" x 0.012"). Reduced elements, that are characterized by only four integration points instead of nine in regular elements, are used since they are less rigid and therefore better reflect the behaviour of the existing material. Results obtained at the integration points are then extrapolated to the nodes.

The split sleeve used in the industrial process could not be modeled since calculations for two plastically deforming bodies (the sleeve and the specimen) showed very poor convergence and required an excessive amount of time. Therefore, the radius of the mandrel, considered in the model as a rigid body, was increased by the thickness of the sleeve and the coefficient of friction at the contact area between the mandrel and the specimen was taken as equivalent to the lubricant inside the sleeve. The stress-strain behaviour of the material obtained from a tensile test was used for determining the flow condition according to the Von Mises criteria.

The only boundary condition of the model is imposed by the axial displacements of the free edge of the specimen. An alternative boundary condition was also examined. This condition limited the axial displacements of the nodes at the exit face of the specimen. The results obtained indicated that the nodes at this face were compressed so severely that the resulting residual stresses were unrealistically high. Flexible supports at the exit face of the model would probably be more representative of the industrial process.

NUMERICAL, EXPERIMENTAL AND ANALYTICAL RESULTS AND DISCUSSION

In this section the results obtained from the finite element analysis will be presented and compared with experimental data. In addition, the results will be discussed in relation to theoretical values obtained from a plane stress and a plane strain approach.

Numerical Results

The proposed numerical model has the particular advantage of having the ability to show the evolution of the coldworking process. Figure 2 illustrates the profile

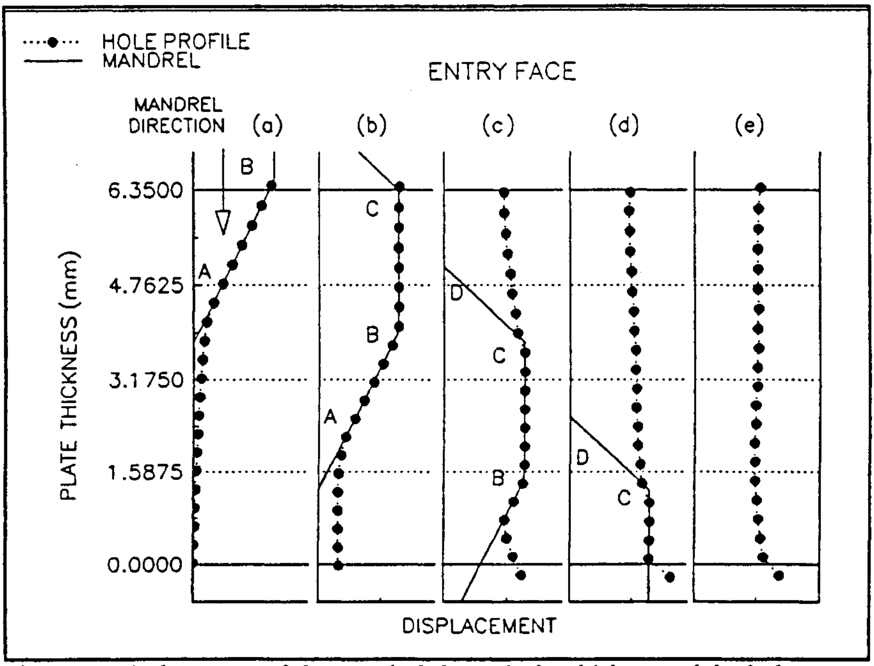

Figure 2: Displacement of the mandrel through the thickness of the hole

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of the hole in five steps as the mandrel is being pulled through the hole. The position of the mandrel is identified by the same letters as in figure 1. The final hole profile, shown in figure 2e, clearly indicates that the coldworking process does not produce a uniform displacement through the thickness of the hole. The exit side of the plate exhibits the largest displacements since the material is pushed towards this face as the mandrel is pulled through. Of the 4% applied expansion, the entry face retained a 3.4% expansion while the exit face retained a 4.3% expansion. The minimum retained expansion has a value of 3.0% and is found at the lower middle portion of the hole profile. A very similar profile was also observed by Cloud [7] who used a three dimensional moiré procedure to measure the variation in retained expansion through the thickness of the plate. These results are in contrast with other numerical methods [8-10] that do not have the capability to show the evolution of the coldworking process.

The residual strain and stress distributions at the centre and just beneath the entry and exit faces of the specimen after cold expansion are shown in figure 3 and figure 4 respectively. The residual strains and stresses found at the entry and exit surfaces near the hole edge were not used since they were inconsistent with respect to the surrounding elements. This may be due to the significant upsetting generated around the hole edge on both surfaces. The distributions found in figures 3 and 4 are associated with the layer 0.64 mm (0.025") below the surface. This distance corresponds to the size of one element.

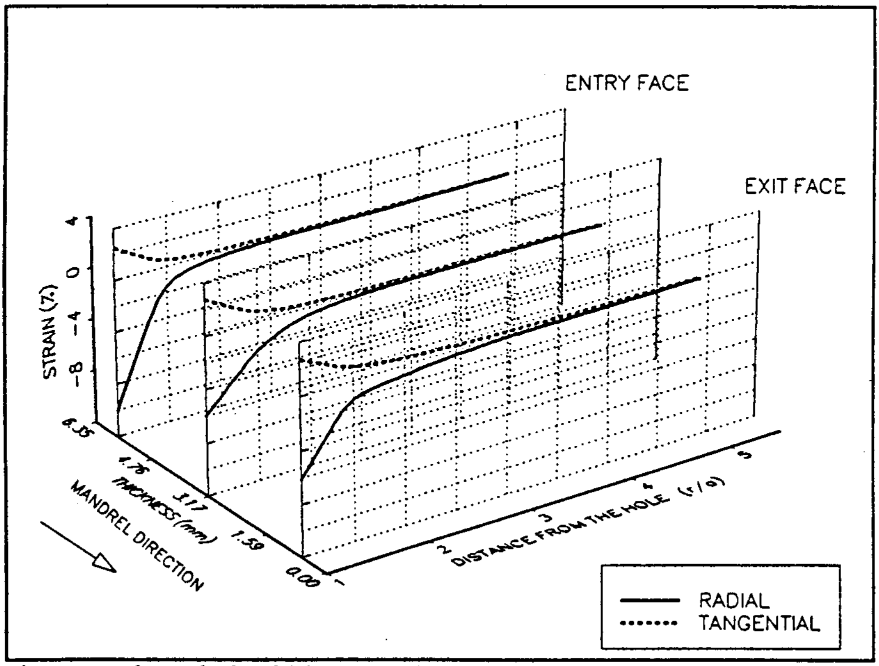

Figure 3: Through the thickness residual strain distribution

The radial residual strain along the hole edge is in compression. The intensity is 46% lower at the mid-thickness and 30% lower at the exit face than at the entry face. This may be due to the behaviour of the material approaching the plane strain flow condition at the mid-thickness. At the exit face, the intensity is less than at the entry face since the geometrical conditions are modified by the accumulation of the material volume by the mandrel movement through the hole. The tangential residual strain distribution is almost unchanged throughout the thickness of the specimen because of the constraining effect of the hole edge. A closer examination of the strain values in the three directions revealed that the condition of incompressibility ($\nu=0.5$) prevails in the plastic zone near the hole edge.

Figure 4 illustrates the difference in the residual stress distribution through

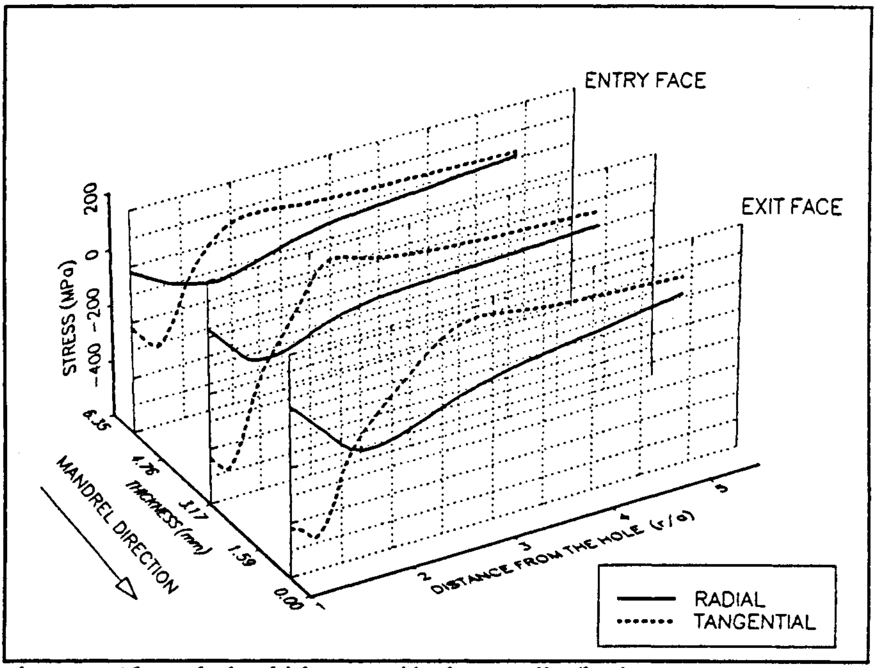

Figure 4: Through the thickness residual stress distribution

the thickness of the plate. The radial residual stresses seem to be dependent on the level of retained expansion. A high level of retained expansion will cause an increase in the pressure exerted by the elastic springback and thereby a more compressive radial residual stress distribution. The tangential residual stresses also depend on the level of retained expansion but seem to be influenced by the amount of material volume carried by the mandrel movement. The combination of radial elastic springback and axial shear generated by the mandrel movement induce hole edge tangential residual stresses that are highly compressive.

Experimental Data

The residual tangential stress distributions obtained from the numerical model

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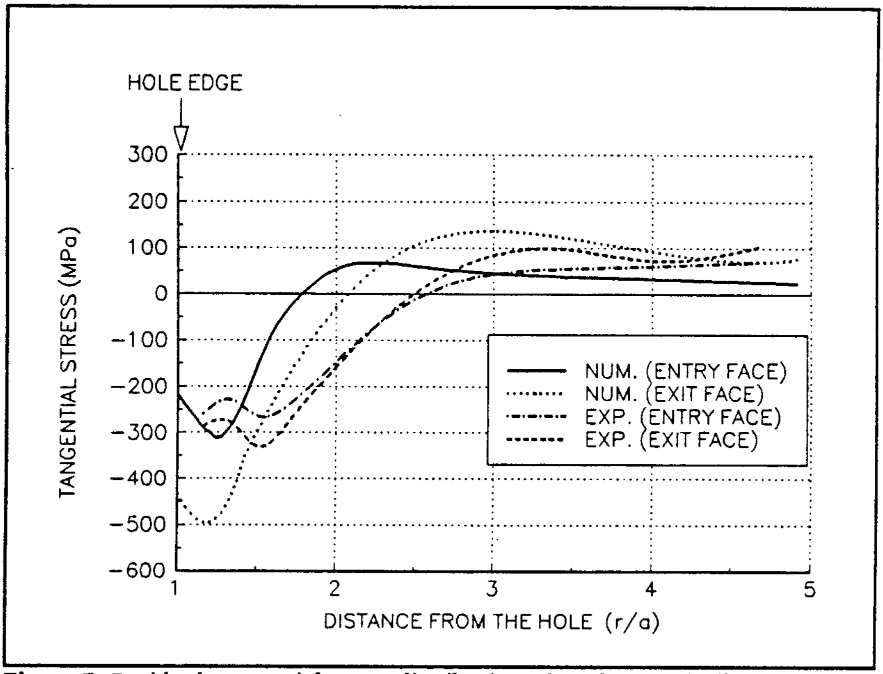

Figure 5: Residual tangential stress distributions found numerically and experimentally.

and measured experimentally on both faces of the specimen exhibit a similar trend as illustrated in figure 5. A reverse yielding zone, characterized by the minimum stress intensity, was observed near the hole edge. Beyond that point, there is a sharp increase of the stress up to the elastic-plastic delimitation (i.e. the highest point on the curve) and finally a gradual decrease to the outside edge of the specimen.

The experimental stress distributions on both faces of the specimen are very similar to each other and seem to have been stretched in the radial direction with respect to the corresponding numerical results. The experimental stress intensities are also smaller than the numerical distributions. This may be explained in part by the fact that the measurements are integrated over a 5.12 mm^2 area. Peak values predicted by the numerical model at the very edge of the hole will be filtered out by the integration over such a large area. For aluminium specimens, a much smaller X-ray beam coming from a more powerful machine would be needed to properly reconstruct the steep gradient of the tangential residual stress at the edge of the coldworked hole.

Results from theoretical models

For the completeness of this study, two theoretical models were also considered. These two models were primarily chosen because of a possible re-yielding around the bore of the hole during unloading. This phenomenon, that is noted in the numerical results as well as in the experimental data, is present when typical expansion levels of the coldworking process are used on aluminium alloys.

One of these models was developed in the plane strain condition while the other was examined in the plane stress condition. Jost's model (plane strain condition) is developed for an annulus of finite dimensions with an elastic-perfectly plastic material response [11]. The Mises yield criterion and the assumption of incompressibility in the plastic zone were used in the model. A non elastic unloading generates the possibility of reverse yielding near the hole edge. The Potter-Ting-Grandt model [12] is based on similar assumptions as Jost's model but applied to the plane stress condition. The expressions for stresses and strains for both models are closed-form and are function of the plastic and re-yielding zones. The size of these zones can be determined from the knowledge of the applied expansion level and are found by numerically solving non-linear equations.

The residual stress distribution obtained from the analytical models are illustrated in figure 6. The model of Potter at al. shows a relatively small re-

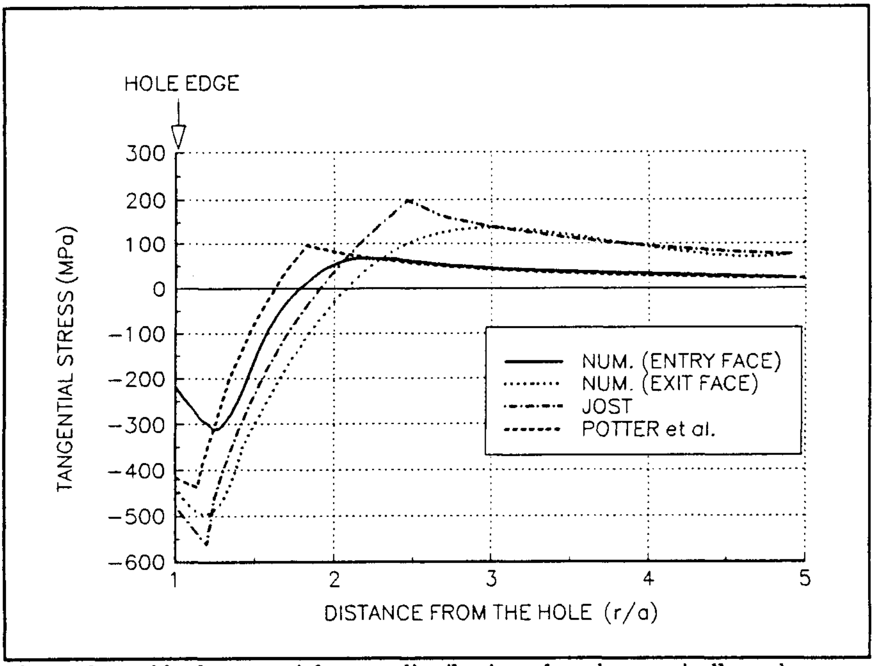

Figure 6: Residual tangential stress distributions found numerically and analytically.

yielding and plastic zone whereas Jost's model prescribes a slightly larger re-yielding zone and a much larger plastic zone. These characteristics are in good agreement with the results obtained by Carey from a finite element study of the coldworking process under both the plane strain and the plane stress condition

[13]. Jost's model gives results that are closer to the numerical results for the exit side of the specimen while the Potter et al. model gives values closer to the entry side numerical results. The proposed model reflects the difference in stress distribution through the thickness of the hole while both analytical models are two dimensional and assume a constant stress distribution. This assumption is clearly not adequate for the coldworking process. Furthermore, the large deformations at the entry face in the region near the hole edge do not support favourably the plane strain assumption while the plane stress condition does not apply at the mid-thickness section.

The 3-D axisymmetric model is not limited by such assumptions and can effectively be used to evaluate the effect of parameters of the colworking process such as interference levels, shape of mandrel, type of lubricant, proximity of holes, quantity of surface upset and the influence of the material thickness and properties on the residual stress distributions. Accurate residual stress distributions will also lead to more realistic fatigue life evaluations and eventually to more confidence in the coldworking procedure.

Improvements to this model such as a finer mesh and the modeling of the sleeve will initially require a more accurate measurement of the residual stress distribution. Such a measurement will then allow a fine tuning of the model that will result in a more reliable tool for studying the coldworking process.

CONCLUSIONS

The experimental data have confirmed that the residual tangential stress distributions on both faces of a coldworked specimen are different. For this reason, the 3-D axisymmetrical finite element study brings a significant improvement over conventional 2-D analysis. The proposed model gave a clear evaluation of the stress and strain distributions through the thickness of the hole, as well as a the hole profile and the extent of the plastic zone. These advantages make this model a powerful tool in the study parameters affecting the coldworking process.

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