

RESIDUAL STRESSES AROUND COLD WORKED HOLES IN 2024-T351 ALUMINIUM ALLOY PLATE SPECIMEN

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ABSTRACT

A finite element simulation study is carried for cold working process ON 2024-T351 aluminum alloys plate. During the process the load is transferred by A mandrel to the plate, which tries to bend a portion of the plate and affects the formation of residual stresses resulting from the cold working process. It is observed that non-dimensional radial residual stress for entrance face and mid thickness plane at the edge of the hole is affected a little by the start of support distance i.e. for various support conditions. Whereas, the tensile radial residual stress for the exit face reduces considerably from a value of 1.05 to approximately zero. The non-dimensional tangential residual stresses for the entrance decrease with start of support distance. Whereas, the non-dimensional tangential residual stresses for the mid plane and exit face reduce from higher compressive stress to lower compressive stress.

1.0 INTRODUCTION

Fatigue cracks generally nucleate and propagate from the uppermost surface of the component, in a region which is subjected to high tensile stresses. The main objective in the aerospace industry is to retard the crack propagation rate and enhance the total life of a component. The objective is well achieved by a good estimation of stress state at the critical region of the components. One of the methods to enhance the fatigue life is cold working of components at the critical regions. In the aerospace structural applications cold working of plate holes is quite common. The Manufacturing Research and Development Organisation of the Boeing Commercial Airplane Company originally developed the cold working process. The cold working process involves plastically deforming the material around the fastener holes, which imparts compressive residual stresses around this region. The cold working process for the fastener hole uses a tapered

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mandrel along with a pre-lubricated disposable sleeve. As the tapered mandrel is pulled through the hole it expands the region around the hole. The cold working or mandrel pre-stressing can be done using mandrels of different configurations. Upon removal of the mandrel from the hole the expanded region unloads resulting a region with residual compressive stresses.

An overview of cold expansion methods by Champoux [1] and Mann et al [2] details about various studies, based on theoretical, finite element analysis and experiments, to obtain the stress and/or strain fields at uncracked cold worked holes. Nadai [3] has developed an analytical solution for the cold expansion of a single hole for ideally plastic material. Hsu and Forman [4] extended the Nadai's model for a strain hardening material. Isotropic linear hardening and reverse yielding were considered in the solution of Rich and Impellizzeri [5] and Jongebreur and Koning [6].

Mangasarian [7] analysed the plastic range in the vicinity of a circular hole in an infinite sheet using J2 deformation theory and incremental theories. The results of J2 deformation theory were assessed in the light of a criterion developed by Budiansky [8] for the acceptability of deformation theories. It has been observed that the two theories do not differ considerably in spite of the stress path being radial. Later, Chen [9] compared the solutions for strain and displacement in a partly plastic annular plate stressed by internal pressure using deformation theory and flow theory for elastic-perfectly plastic material obeying Mises yield criterion. The results obtained for inner displacement on the basis of deformation theory were within 5% of flow theory. Although there are numerous exact solutions available for an elastic-perfectly plastic open-ended cylinder abiding by the von Mises criterion, theoretical solutions for strain hardening material obeying the Mises criterion are not many. Lu and Hsu [10] and Wanlin [11], on the basis of J2 deformation theory using modified Ramberg-Osgood law, obtained an exact elasto-plastic solution for stresses in a thin disc with internal pressure. Recently, Xin-lin [12] and Arora et al [13] developed closed form solutions for elastic-plastic open-ended cylinder and thin plate with a hole, respectively using deformation theory and von Mises yield criterion.

Link and Sanford [14] used moiré interferometer and obtained the residual strain field surrounding a single split-sleeve cold expanded hole in 6.35 mm thick 7075-T651 aluminium alloy plates. They concluded that three-dimensional analysis is more appropriate for predicting the residual strain field surrounding cold-expanded holes. Cook and Holdway [15] used the x-ray diffraction technique to measure the radial and hoop residual stresses around the cold expanded fastener holes in 7050-T76-aluminium alloy. Poussard et al [16] carried out two-dimensional and axis-symmetrical finite element analyses to evaluate the residual stress field around a cold expanded hole in 2024-T351-aluminium alloy. They have concluded that the plane stress and plane strain assumptions used in the earlier analytical models did not satisfactorily approximate the three dimensional residual stress fields obtained from the finite element simulations. Recently, Bernard et al [17] and Pavier et al [18] conducted

an axis-symmetric analysis of the cold expansion process, accounting for contact between the mandrel and the hole surface. The relative axial deformations obtained by Pavier's et al [18] finite element simulation over the surface around the cold worked holes have shown a good agreement with the x-ray diffraction experimental results. Of late split mandrel cold working process suggested by Leon [19] is being used which reduces the risk of formation of shear cracks at the ridge formed by split sleeve.

One of the major requirements in cold hole expansion of fastener holes is the avoidance of surface damage introduced at the interface during the cold working process. To overcome this difficulty, a well-lubricated split sleeve is used in between the hole surface and the mandrel. A number of parameters influence the residual stress field e.g. process, geometrical, material and loading [20]. Apart from the optimum expansion level the loading and the geometry are very important parameters in the cold expansion process.

The purpose of this investigation is to study the residual stress behaviour at the edge of the hole for a sleeveless cold working process in a 2024-T351 plate specimen with 6.35 mm diameter hole. A recommendation for the optimum support condition is made which represents the actual cold working experiments involving the split sleeve method.

2.0 FINITE ELEMENT MODEL

The material of the specimen used in this investigation is 2024-T351 aluminium alloy plate of 6 mm thickness. For a material with isotropic hardening behaviour, a power law relationship was used to generate stress-strain data points. The deformation response for these cases is described by equation (1),

$$\varepsilon = \frac{\sigma}{E} \quad \text{for } \sigma \leq \sigma_y$$

and

$$\varepsilon = \frac{1}{E} \left(\frac{\sigma^{n+1}}{\sigma_y^n} \right) \quad \text{for } \sigma \geq \sigma_y \quad (1)$$

The specimen is considered to be a circular disc of outside radius of 50 mm and inner radius of 3.175 mm. The 2024-T351 aluminium alloy has the following mechanical properties in the longitudinal rolling direction: Young's modulus = 71.6 GPa, Poisson's ratio = 0.28; mass density = 2.78 g/cc, yield stress $\sigma_y = 365$ MPa. Although the material observed experimentally is a little anisotropic in the transverse direction, for this analysis it is considered to be isotropic. The plastic tensile and compressive tangent moduli m and m' have been assumed to be the same and their value is 1.576 GPa. The material for the mandrel is steel with Young's modulus of 210 GPa and Poisson's ratio of 0.30. The geometry of the

model specimen and the mandrel is shown in Figure 1 and it represents the set-up of the cold working process.

Axis-symmetric finite element analysis is carried out to predict the residual stress distribution surrounding fastener hole subjected to 4 per cent cold working, the typical level of cold expansion used in the aerospace industry. The diameter of the mandrel, D_2 is 6.350 mm and it was calculated by the following equation (2) for 4 per cent nominal expansion, χ ,

$$\chi = \frac{D_2 - D_1}{D_1} \times 100 \quad (2)$$

where

D_1 is the initial diameter of the hole

D_2 is the diameter of the mandrel

The Finite Element code LUSAS version 13.1 has been used to simulate the three-dimensional cold expansion process. From LUSAS finite element library elements 4-noded isoparametric axis-symmetric solid continuum elements have been used for the analysis. The elements use a standard integration scheme of 2X2 Gauss points. The model is represented by 644 axis-symmetric solid continuum elements out of which 500 elements are used for the specimen and 144 for the mandrel. A higher intensity of elements was used for the region close to the hole edge. Due to the contact between the mandrel and the specimen, slide lines were used at the interface between the mandrel and the hole with zero coefficient of friction.

A prescribed displacement load (PDSP) equal to 14 mm was imparted to the mandrel in the forward direction simulating the total movement of the mandrel through the plate thickness. This PDSP is required to clear the plate specimen after the cold-working process is over. The PDSP was assigned to the mandrel surface. The mandrel was initially positioned so that it would touch the inner surface of the hole and the cold working simulation was carried out by incrementing the position of the nodes on the mandrel surface. For the automatic incrementation and iteration procedure in LUSAS-13.1 a total of 114 iterations were used to pull the mandrel through the hole completely.

In this investigation the effect of the support conditions on the residual stresses at the hole edge is also analysed. The geometrical details of the support conditions are given in Figure 2 and the support distance parameters are given in Table 1. The finite element mesh for the specimen and the mandrel is given in Figure 3. For the support conditions considered in this investigation the nodes on the base of the specimen only were restrained from moving in the vertical direction. However for all the support conditions considered the region corresponding to the cold expansion of 4% is left unsupported to allow the movement of the mandrel.

3.0 FINITE ELEMENT RESULTS AND DISCUSSIONS

The non-dimensional radial residual stresses as a function of the non-dimensional radial distance (normalised by hole radius, a) from the hole edge for eight different models have been obtained. As an example the non-dimensional radial residual stress distribution and the non-dimensional tangential residual stress distribution have been shown in Figure 4 for support condition-3. The details of the other support conditions are given elsewhere [21]. For each model support condition a set of three respective curves corresponding to the residual stress distribution on the entry face, at the mid-thickness and on the exit face of the specimen have been obtained. It is observed that the radial residual stress distribution for entrance face is of tensile nature for some length from the edge of the hole and then remains compressive throughout the remaining part of the specimen region for all the support conditions. Whereas the radial residual stress distribution for the exit face shows a spurt in value, an unusual phenomenon, which depends on the support condition. It was noted that the highest value of the radial residual tensile stress on the entrance face was obtained for the support-1 and the magnitude of this maximum radial residual tensile stress decreases with increase in the start of the support position from the edge of the hole. The lowest value of radial residual tensile stress has been obtained for the support-8 and its value is 258.9 MPa. On the other hand the magnitude of the spurt in value of radial residual compressive stresses varies with the support condition and it finally reduces to zero value for support condition 7 and 8. This suggests that if the support condition is used with support starting from 15 to 20 mm from the edge of the hole, no spurt in the radial residual stress data is observed.

The non-dimensional tangential residual stresses [21] also have been calculated with different support conditions. In general for the entrance face of the specimen the nature of the tangential residual stresses is tensile for some distance from the edge of the hole and then it changes its sign from tensile to compressive residual stress beyond the distance mentioned above. For the mid-thickness, the tangential residual stresses are of compressive nature near the edge of the hole, whereas for the exit face a spurt in tangential compressive stresses has been observed. The distribution of tangential residual stresses [21] at the entrance face suggests the superiority of support conditions 7 and 8 as compared to support conditions 1 to 6 with respect to residual stresses induced during the cold-working process. A better spread of tangential residual compressive stresses has been observed for the support conditions 7 and 8 for the entrance face. For support condition 8, the residual stresses are of compressive nature right from the edge of the hole for the entrance face. The results obtained for residual stresses at the mid thickness with increase in radial distance for different support conditions were plotted in single figure [21] and the results appear in a narrow scatter band. The spread of compressive residual stresses is beneficial for better fatigue life of machine components where it acts as a barrier to crack growth.

The non-dimensional radial residual stress at the edge of the hole for the entrance face, mid thickness plane, and the exit face versus support distance from the edge of the hole is given in Figure 5. The non-dimensional radial residual stress for the entrance face is around 0.2 for support condition-1 and it varies a little as the start of support distance from the edge of the hole increases. Also the non-dimensional radial residual stress at 0.15 mm from the edge of the hole decreases from 1.05 to 0.8 for various support conditions. It is observed that the amount of non-dimensional radial tensile residual stress decreases which is responsible for retarding the crack propagation rate. At the mid thickness plane/face non-dimensional radial residual stress increases a little with the increase in support distance, and then remains virtually constant for all the support conditions. The variations in the amount of residual stress with the support distance from support condition-1 to support condition-2 are quite perceptible. The variation in non-dimensional radial residual stress (Figure 5) with support distance at the exit face is of different nature. For the exit face the tensile residual stresses at the edge of the hole decreases from 1.05 to practically zero value with support distance from the edge of the hole for different support conditions. On the other hand the non-dimensional radial residual stress value for a location 0.15 mm away from the edge of the hole first decreases and then increases with increase in support distance. It has been observed that for all the three faces the variation in the non-dimensional radial residual stress is perceptible till the support distance of about 20mm.

The non-dimensional tangential residual stress at the edge of the hole decreases with the increase in start of support distance for the entrance face as shown in Figure 6. The residual stresses are tensile in nature for support conditions 1 to 4 while it changes its sign for support conditions 6 to 8. A somewhat similar behaviour is observed for residual stresses at 0.15 mm away from the edge of the hole for various support conditions. At the mid thickness plane non-dimensional tangential residual stress value reduces a little from support condition-1 to support condition-2 and then remains practically constant for all other support conditions. On the other hand the non-dimensional tangential residual stress at 0.15 mm from the hole varies from its compressive value to tensile value. However it is observed that the shift in the sign of the residual stress takes place after support condition-5. The non-dimensional tangential residual stress for the exit face mathematically increases with support distance i.e. reduces from higher compressive stress to lower compressive stress. Its value becomes constant beyond the support condition-6. At 0.15 mm away from the hole edge a similar behaviour is observed for tangential residual stresses for the exit face.

From the observed data one can comprehend that for higher fatigue life the residual stresses should have as low as possible a value when they are of tensile nature and as high as possible when they are of compressive nature for all the entrance face, mid plane/face, and exit face of the specimen after cold working operation. In view of having the optimum conditions for the support it is

recommended that the support condition-7 is the most appropriate for having good overall fatigue properties of the material.

4.0 CONCLUSIONS

On the basis of a finite element simulation study carried out the following conclusions are drawn,

- i) The non-dimensional radial residual stress for entrance face and mid thickness plane at the edge of the hole is affected a little by the start of support distance i.e. for various support conditions. Whereas, the tensile radial residual stress for the exit face reduces considerably from a value of 1.05 to approximately zero.
- ii) The non-dimensional tangential residual stress for the entrance decrease with start of support distance. Whereas, the non-dimensional tangential residual stresses for the mid plane and exit face increase mathematically with support distance i.e. reduces from higher compressive stress to lower compressive stress and its value remains constant beyond the support condition-6.
- iii) It is recommended that the start of the support distance should be in the range of 10 to 20 mm from the edge of the hole, which are for support condition-7 and support condition-8 respectively.

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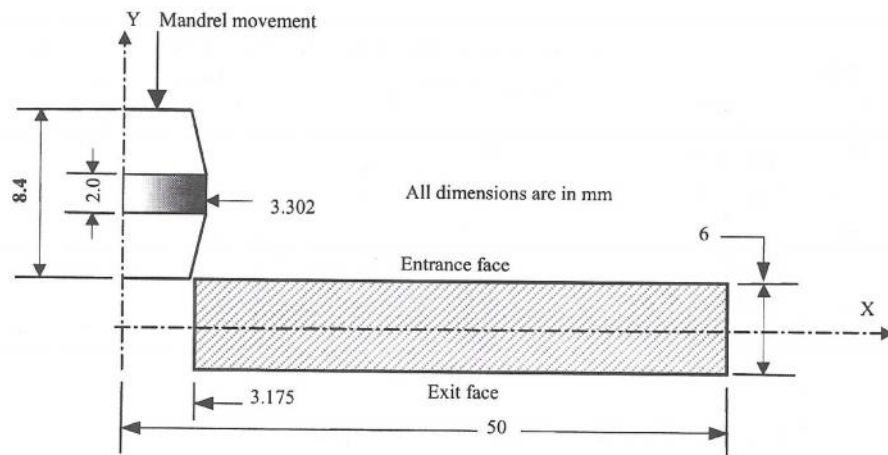


Figure 1

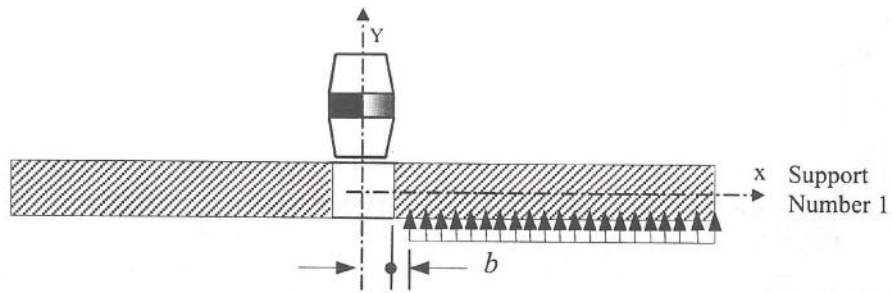


Figure 2

Table 1: Support distance parameters

S. No.	Case	Distance from the hole edge, b (mm)	Ratio = (Support distance, b / Hole radius, a)
1	Support-1	3.302	1.0400
2	Support-2	3.500	1.1024
3	Support-3	4.000	1.2598
4	Support-4	5.000	1.5748
5	Support-5	6.000	1.8897
6	Support-6	7.500	2.3622
7	Support-7	10.000	3.1496
8	Support-8	20.000	6.2992

$a = 3.175$ mm (radius of the hole in the plate specimen)

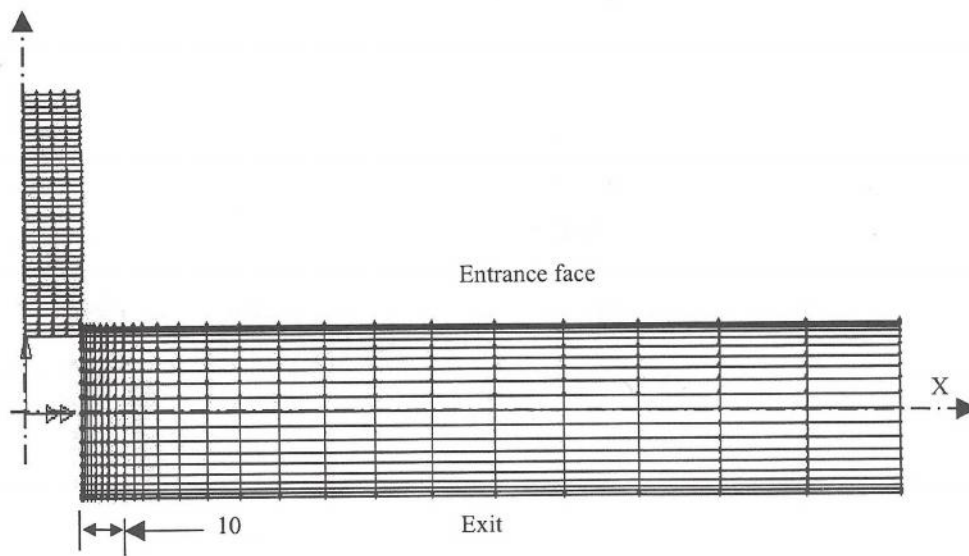


Figure 3 The finite element mesh for the plate specimen and mandrel

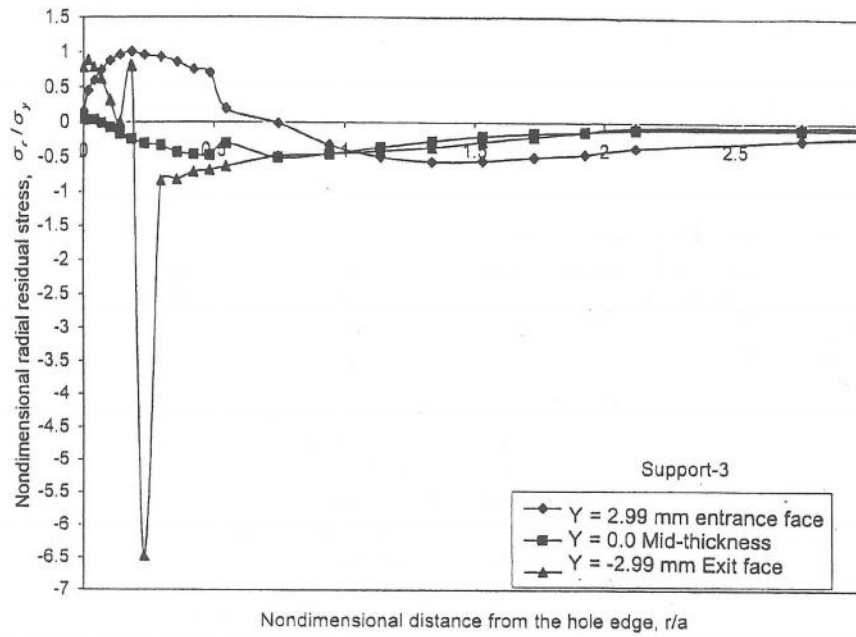


Figure 4a Nondimensional radial residual stress distribution

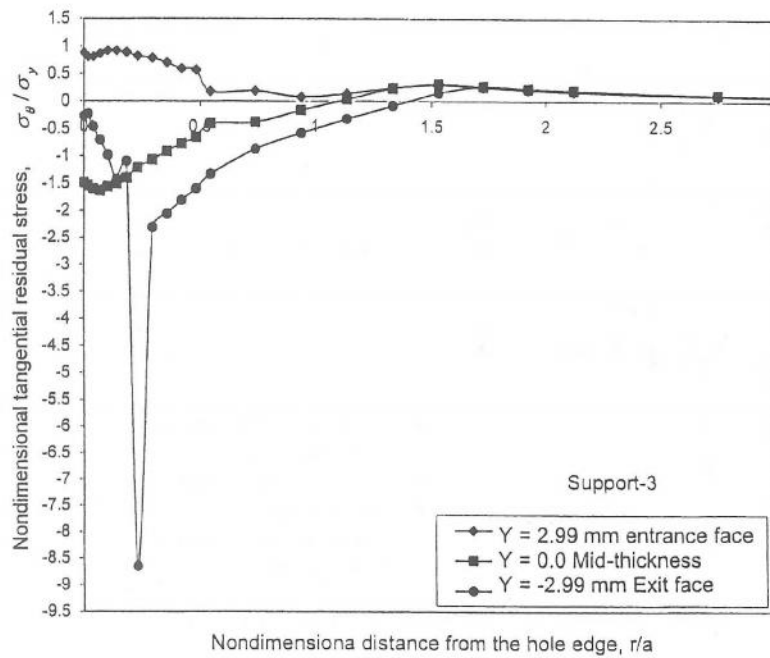


Figure 4b Nondimensional tangential residual stress distribution

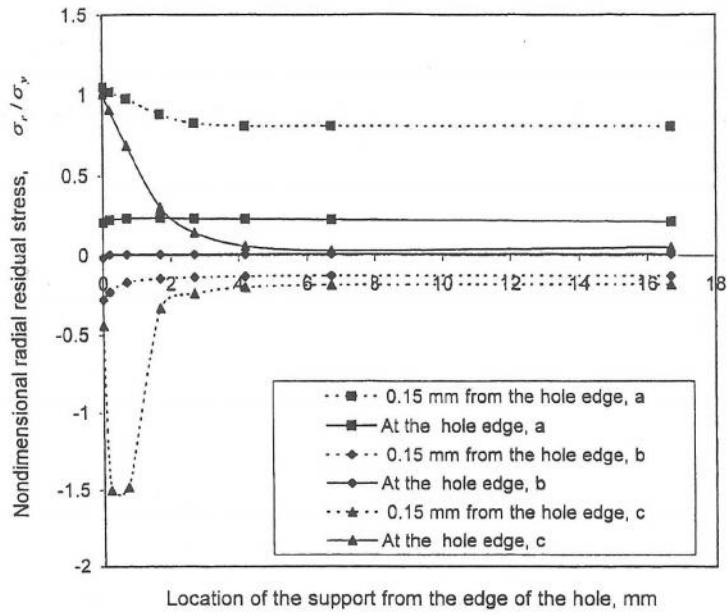


Figure 5 Non-dimensional radial residual stress vs support position (a - entrance face, b - mid-thickness and c - exit face)

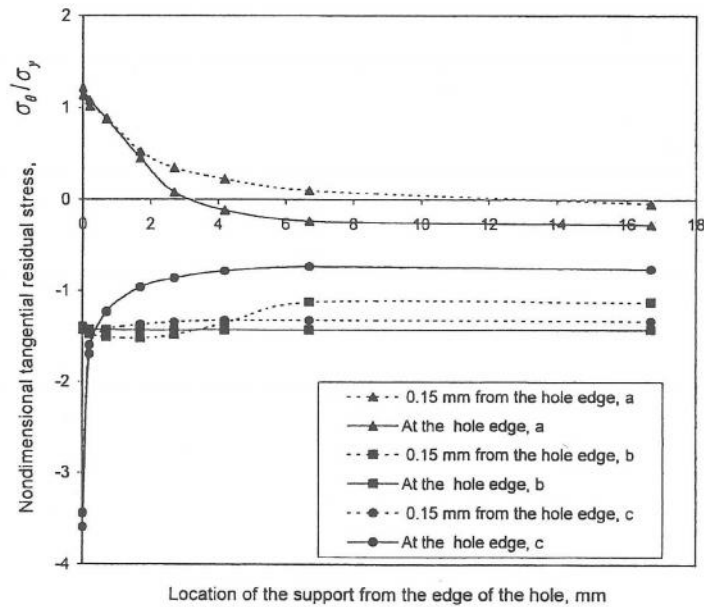


Figure 6 Non-dimensional tangential residual stress vs support position (a - entrance face, b - mid thickness and c - exit face)