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Finite Element Simulation of Residual Stresses in Cold-expanded Plate

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ABSTRACT

In the aerospace industry, the fastener holes are widely present because various mechanical parts need to be connected by rivets or bolts. These holes experience external forces which cause a tensile stress on the surface resulting in fatigue cracks and eventually fatigue failure of the structure. To alleviate this problem, cold expansion method has been used to improve the fatigue behavior of structures by inducing compressive residual stresses around the holes by forcing a tapered mandrel through the fastener hole that is slightly smaller than the mandrel. In this study, finite element simulations had been carried out for cold expansion process in order to determine the residual stress fields around two cold-expanded holes by varying the centre distance between two holes and also the thickness of the material. Moreover, the effect of through thickness position has also been investigated by considering the residual stresses distribution at different positions such as at the entrance face, at the middle of the thickness and at the exit face of the material. Aluminium alloy 7075-T6 was used as the material for the model simulated in ANSYS. The results showed that as the distance between the adjacent holes increased, the residual stresses decreased. Moreover, the simulation also highlighted the effect of the plate thickness and the through thickness position on the residual stresses distribution. The compressive residual stresses increased as the plate thickness increased. Meanwhile, the results at the mid-thickness were higher than the results at the entrance and exit faces.

Key words: Compressive residual stresses, nonlinear analysis, adjacent holes distance, plate thickness, aerospace industry

INTRODUCTION

Various techniques have been introduced in aerospace industry to improve the fatigue life of fastener joints. These joints which are mainly connected by rivets, or bolts and nuts through the fastener holes, allow the parts to be assembled and disassembled easily. The presence of fastener holes which act as stress concentrators significantly reduces the fatigue life of these fastener joints. Shot peening (Kim *et al.*, 2001) and split sleeve cold expansion methods are two widely used methods in aerospace industry to increase the fatigue life of fastener joints (Ball and Lowry, 1998).

In aerospace industry, fastener holes are normally subjected to expansion ratios between 2 and 6% (Papanikos and Meguid, 1998). Split sleeve cold expansion technique is usually employed to improve the fatigue life of fastener joints (Mahendra Babu *et al.*, 2008). This technique enhances the fatigue life of fastener joints by developing compressive residual stresses in the area where the fatigue cracks are expected to initiate.

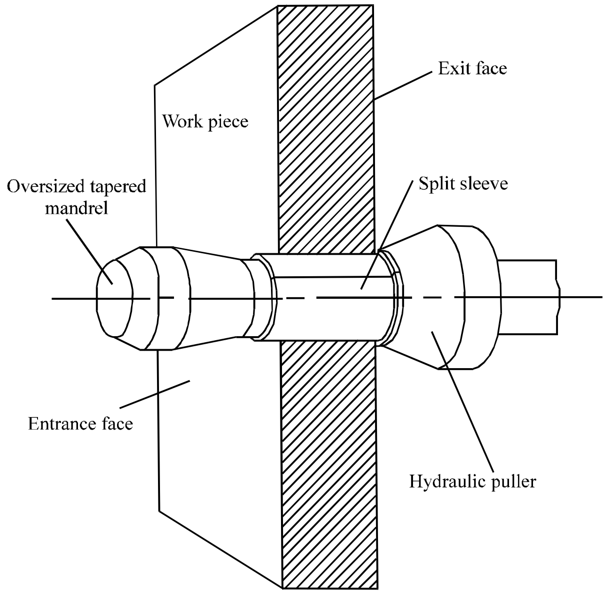

Fig. 1: The schematic representation of the split sleeve cold expansion process (Pavier *et al*., 1998)

The schematic of the split sleeve cold expansion process is shown in Fig. 1. The process of split sleeve cold expansion method is fairly simple where it uses a tapered mandrel which is pre-fitted with a lubricated split sleeve that goes through the fastener hole and will develop compressive residual stresses as the material is plastically deformed through the hole's edge. This compressive residual stress remains tangential to the hole's edge as the mandrel is being drawn out from the hole. The compressive stress will reduce the initiation and growth of a fatigue crack when the material is subjected to cyclic loads. The use of split sleeve is to reduce mandrel pull force and to ensure correct radial expansion of the hole.

The residual stress distribution depends on many parameters such as the cold expansion ratio, material properties, the position and the size of the hole (Kim *et al*., 2002). Ozdemir and Hermann (1999) noticed that the change in plate thickness could result in a different distribution of the residual stresses. Nigrelli and Pasta (2008) investigated the residual stress distribution of a plate at different through-thickness positions (entrance face, mid-thickness and exit face), the effect of the plate thickness and the effect of the split sleeve. The finite element simulations of residual stresses were carried out using 5083-H321 aluminium plate at 4% nominal interference to investigate the cold expansion behaviour. Link and Sanford (1990) studied the residual strain fields surrounding a single split-sleeve cold expanded hole in 7075-T651 aluminium plates. They concluded that two-dimensional analysis is not capable to predict the residual strains surrounding cold-expanded holes accurately.

Therefore, in this study, the effect of adjacent holes in the distribution of residual stresses using cold expansion process was investigated by varying the centre distance between holes (c/d). The diameter of the holes was kept constant but with varying c/d ratios of 2, 4 and 6. Moreover, the effect of plate thickness was also examined. The ratio between the thickness and the hole's diameter (t/d) was varied at 1, 2 and 3. Aluminium alloy 7075-T6 was used as the material for the model simulated using ANSYS.

FINITE ELEMENT MODELING

In this study, the model employed was a plate containing two holes each with diameter, d = 6 mm and a centre distance c between the holes, as shown in Fig. 2. The dimensions of the plate were: width w = 45 mm, height h = 45 mm and thickness over diameter ratio t/d = 1, 2 and 3. Central distances between the two holes were varied by using the c/d ratio of 2, 4, an 6.

In view of symmetry, only one quarter of the plate was used for the two-dimensional (2-D) and three-dimensional (3-D) modeling in ANSYS (Wei and Karuppanan, 2011). The dimensions used were: width w = 22.5 mm, height h = 22.5 mm and hole diameter d = 6 mm, as shown in Fig. 3.

The material properties used in the model are as shown in Table 1. True stress versus true strain curve for 7075-T6 Aluminium alloy is as shown in Fig. 4.

Table 1: Mechanical properties of 7075-T6 Aluminium alloy

Mechanical properties	Unit
Yield strength	506 MPa
Ultimate tensile strength	582 MPa
Modulus of elasticity	72 GPa
Poisson's ratio	0.32

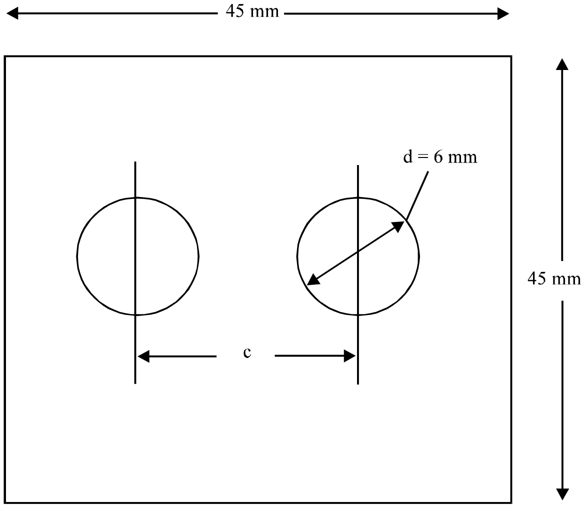

Fig. 2: Dimension of the model

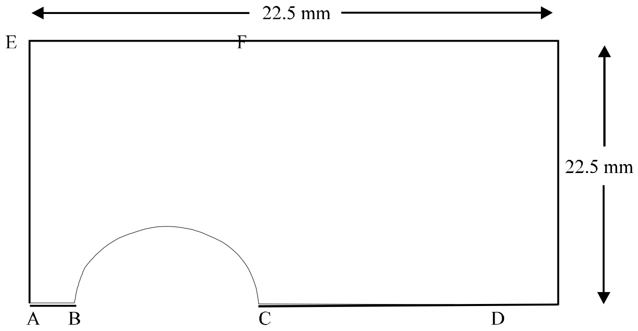

Fig. 3: One quarter of the plate

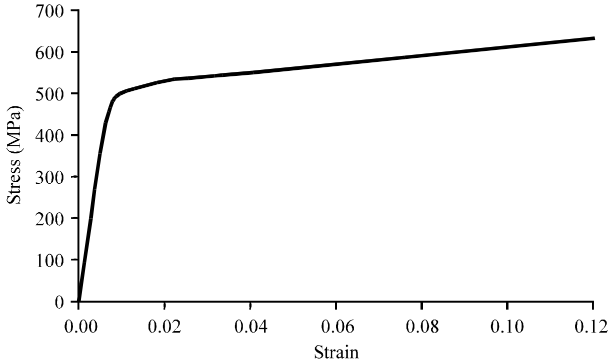

Fig. 4: True Stress versus true strain curve for aluminium alloy 7075-T6

In this study nonlinear analyses were carried out. The element used for the 2-D and 3-D models were PLANE82 and SOLID92, respectively. Both element types can tolerate irregular shapes without much loss of accuracy and well suited to model curved boundaries. The symmetric boundary conditions were imposed along lines AB, CD and AE, whilst lines DF and EF were fixed by constraining all degrees of freedom. The inner surface of the hole was then subjected to incremental pressure loading until diameter increment of 0.24 mm (4% cold expansion ratio) during the simulation.

RESULTS AND DISCUSSION

Two-dimensional (2D) finite element modeling with different adjacent holes distance: In order to investigate the effect of the distance between the holes on the residual stress distribution, 2D finite element modeling was used. The plate contained two 6 mm diameter holes with a central distance (c). The residual stresses distribution for c/d = 2 is shown in Fig. 5. Compressive residual stresses were observed around the hole with decreasing magnitude away from the hole.

Figure 6 shows the variation of the stress distribution for different distances between adjacent holes. The highest compressive residual stress magnitude occurred when c/d = 2. Furthermore, as the distance between the holes increased, the residual stresses will decrease until when the c/d = 6 where the graph plot for c/d = 6 is almost the same as for c/d = 4. We can conclude that there is no influence on the residual stresses if the distance between the holes is greater than six times the hole's diameter. Kim *et al.* (2004) observed the similar trend in Al6061-T6. They concluded that the residual stresses adjacent to one hole are not influenced by another if c/d ratio is greater than 4 for simultaneous cold expansion process and is greater than 5 for sequential cold expansion process.

Cold expansion method is a process to develop compressive residual stresses that is tangential to the hole's edge. The 2-D model was not capable to accurately predict the residual stresses because the tangential residual stresses distribution cannot be found from 2-D models. It can be found only in three-dimensional (3-D) model. Furthermore, the 2-D model is also not capable to account for friction as well as surface roughness variations through the thickness of the plate during the cold expansion process. These limitations have also been reported by Papanikos and Meguid (1998, 1999) which motivated for the 3-D finite element modeling shown below.

Three-dimensional (3-D) finite element modeling with different adjacent holes distance: For 3-D modeling, the central distances between the two holes were varied by using the c/d ratios of 2, 4 and 6. The residual stresses distribution for c/d = 2 in 3-dimension is

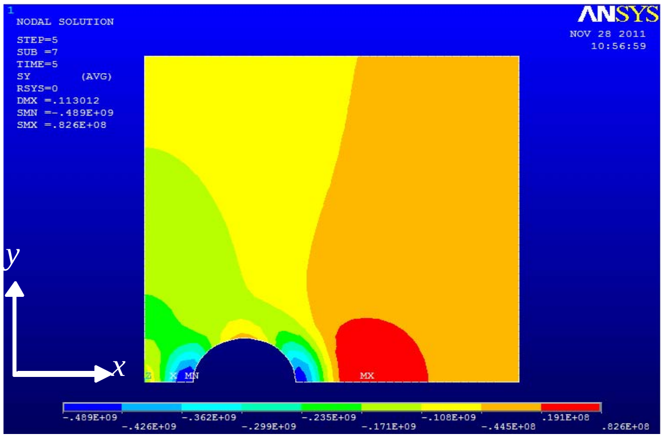

Fig. 5: Stress contour distribution in y-direction for c/d = 2

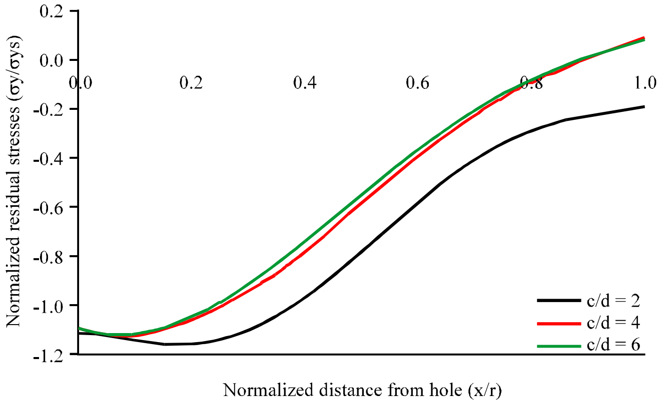

Fig. 6: 2-D stress distribution in y-direction for c/d = 2, 4 and 6

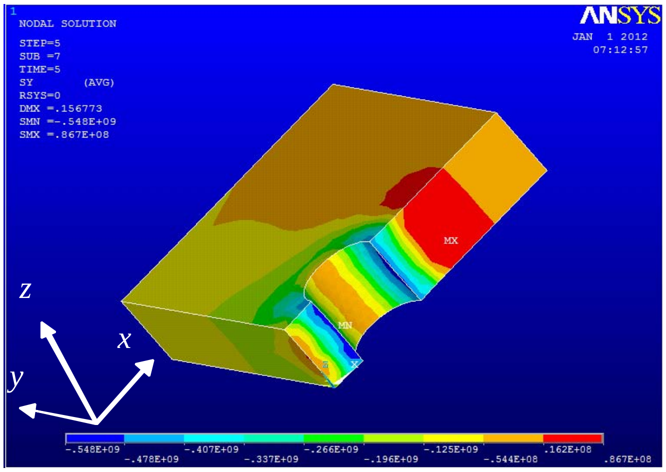

Fig. 7: 3-D stress contour distribution for c/d = 2

as shown in Fig. 7. Similar to 2-D analysis, compressive residual stresses were observed around the hole with decreasing magnitude away from the hole.

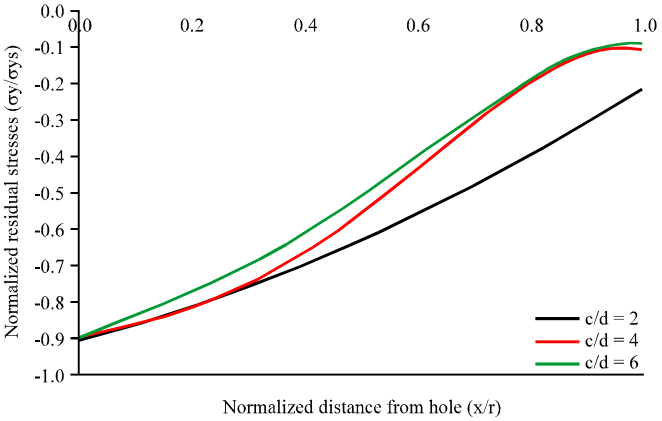

Fig. 8: 3-D stress distribution in y-direction for c/d = 2, c/d = 4 and c/d = 6

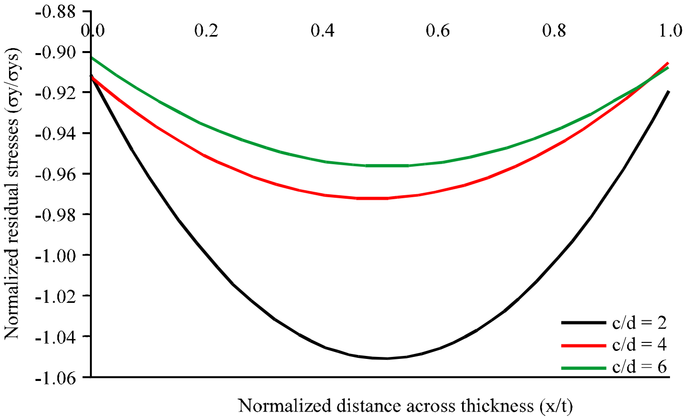

Fig. 9: Tangential residual stresses distribution in y-direction for c/d = 2, c/d = 4 and c/d = 6

Figure 8 shows the variation of the stress distribution for 3-D models. The stress distribution is at the entrance face of the plate. The highest stress distribution occurred when c/d = 2. It is also apparent that the centre distance of the two cold expanded holes can lead to a significant change in the compressive residual stresses distribution. This observation was also reported by Papanikos and Meguid (1999). Figure 8 also shows that an increase in the centre distance between the cold expanded holes results in a decrease in the compressive residual stresses around the cold expanded holes.

In addition, the normalized tangential residual stresses at point B of the plate model (refer Fig. 3) were also analyzed. Tangential residual stresses at point B were plotted across the thickness of the specimen for the different adjacent hole distances (c/d = 2, 4 and 6). Figure 9 shows the tangential residual stresses distribution for different adjacent holes distance with 4% cold expansion ratio. From the figure, we can see that the tangential residual stresses distribution distinctly varied for different adjacent holes distance. The highest tangential residual stresses distribution was when c/d = 2. It is also obvious that for different adjacent holes distances, the tangential residual stresses are highest at mid-point due to plane strain effects at mid-thickness. The through thickness variation in residual stresses magnitude was also reported by Mahendra Babu *et al*. (2008), Ismonov *et al*. (2009) and Houghton and Campbell (2012). They also found that the highest value of residual stress is at the mid-thickness of the plate.

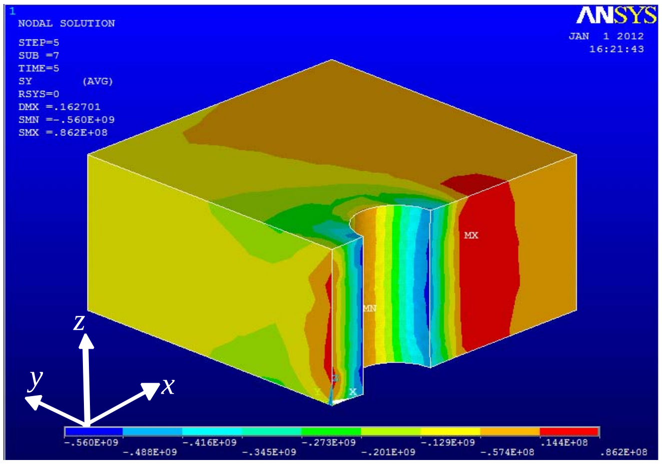

Fig. 10: 3-D model for c/d = 2 and t/d = 2

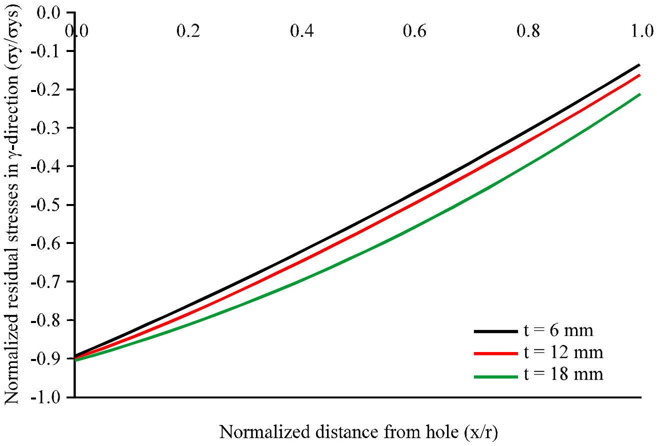

Fig. 11: Residual stresses distribution in y-direction for c/d = 2 with t/d = 1, t/d = 2 and t/d = 3

Three-dimensional (3-D) finite element modeling with different plate thickness: For this analysis, the residual stresses in cold-expanded plates with different thicknesses have been investigated using 3D finite element modeling. The central distances between two adjacent holes were varied using the ratio of c/d = 2, 4 and 6. The plate thicknesses were also varied using t/d = 1, 2 and 3. This analysis was focused at the hole edge. The residual stresses distribution of the 3D model for c/d = 2 and t/d = 2 is shown in Fig. 10.

Figure 11 shows the residual stresses distribution for c/d = 2 and t/d = 1, 2 and 3. The compressive residual stresses increased as the plate thickness increases from 6-18 mm. It is evident that the highest compressive residual stresses are when the plate thickness is 18 mm. From Fig. 11, the maximum compressive stress was found at the surface of hole's edge. The state of stress changes from the plane-stress to the plane-strain condition with the increasing thickness. Hence, the residual stresses produced after cold expansion process becomes more compressive. The plate thickness is very effective in increasing the maximum compressive stress in the cold expansion

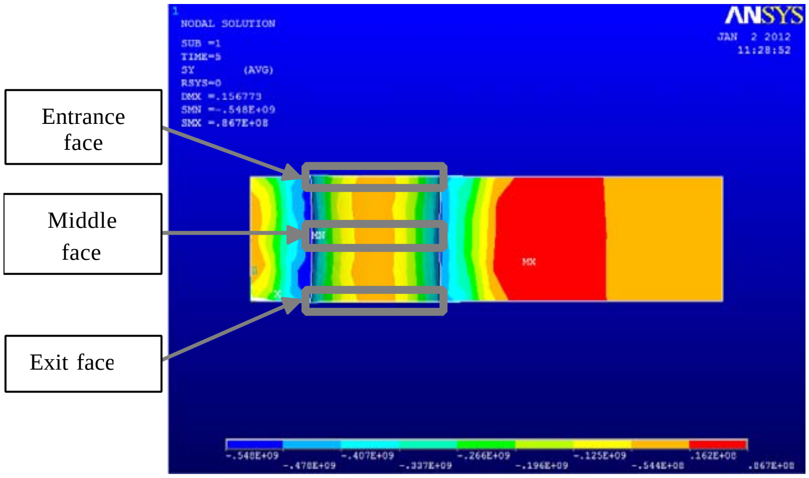

Fig. 12: Through thickness position

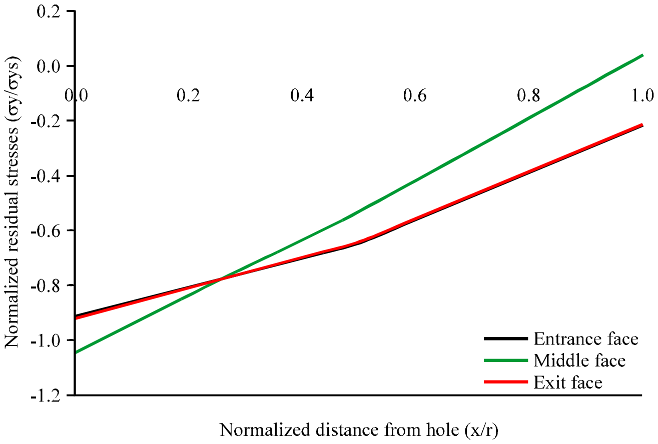

Fig. 13: Residual stresses in y-direction at through thickness position

process. Ozdemir and Hermann (1999) and Nigrelli and Pasta (2008) also reported that the residual stresses become more compressive with the increase in the thickness of the plate.

The similar results were also observed for c/d = 4 and c/d = 6. However, the compressive residual stresses distribution for different plate thickness appears to differ slightly as compared to the results of c/d = 2.

Three-dimensional (3-D) finite element modeling at different through thickness positions (entrance face, middle face and exit face): In order to investigate the effect of different through thickness position on the residual stress distribution, 3D finite element modeling was used. The central distance between the two holes were fixed at c/d = 2. The plate thickness was set to 6 mm (t/d = 1). This analysis was focused at the hole's edge. Figure 12 shows the different through thickness position at the hole's edge. The results of the 3-D Finite Element Modeling using ANSYS with 4% cold expansion ratio for different through thickness position (entrance face, middle face and exit face) are shown in Fig. 13.

From Fig. 13, the compressive residual stresses at the entrance and the exit faces were lower than the stresses at mid-thickness. Low compressive residual stresses at the entrance and the exit faces were caused by the shear stress from the axial movement of the mandrel (applied pressure). Furthermore, for 6 mm plate thickness, the compressive residual stresses at the entrance face are similar to those at the exit face. These results showed that a relatively homogeneous distribution of compressive residual stresses was obtained for 6 mm plate thickness.

CONCLUSIONS

Two-dimensional and three-dimensional Finite Element Analysis (FEA) simulations of cold expansion for different adjacent holes distance were carried out using ANSYS on 7075-T6 aluminium plates. The FEA was carried out to determine the effect of the distance between adjacent holes on residual stresses. The simulation process was performed at 4% cold expansion ratio (radius increment of 0.125 mm) and the distance of the adjacent holes were varied as c/d = 2, 4 and 6.

From the results of the simulation, we can conclude that when the distance between the holes is increasing, the residual stresses will decrease. Furthermore, when c/d = 2, the residual stresses is the highest.

The effect of different plate thickness on the residual stress distribution was also investigated. We can conclude that the compressive residual stresses increase as the plate thickness increase. Moreover, the different through thickness position was also investigated and the result showed that the compressive residual stresses at the entrance face and the exit face were lower than the stresses at the mid-thickness.

It can be concluded that the adjacent holes and the plate thickness does effect the distribution of the compressive residual stresses. Cold expansion method is a useful method to increase the fatigue life of a material.

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