

Finite element analysis of residual stress in cold expanded plate with different thickness and expansion ratio

Kamarul Arifin Shariffudin¹, Saravanan Karuppanan¹ and Santosh S Patil^{1,2}

¹Mechanical Engineering Department, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia.

²Mechanical Engineering Department, Manipal University Jaipur, 303007, Dehmi Kalan, Jaipur, India

*Corresponding author: santosh045@gmail.com

Abstract. Cold expansion of fastener/rivet holes is a common way to generate beneficial compressive residual stress around the fastener hole. In this study, cold expansion process was simulated by finite-element method in order to determine the residual stress field around two cold expanded holes by varying the plate thickness and expansion ratio of the hole. The model was developed in ANSYS and assigned to aluminium alloy 7475-T61 material model. The results showed that the residual stress become more compressive as the plate thickness is increased up to $t/d = 2.6$ and decreased for further level of thickness. In addition, the residual stress at the edge of the hole become more compressive as the expansion ratio is increased up to 4.5% and decreased for further level of expansion. This study also found that the residual stresses near the entrance and the exit face of the plate are less compressive than the residual stresses on the mid-thickness of the plate.

1. Introduction

Variety of techniques has been developed to enhance the fatigue life of fastener or riveted structural joints used in aircraft industry. These type of joints are widely used since most of the joints are connected by rivets or bolts through the fastener holes that exist on the aircraft structure. This type of joint will help the parts to be assembled and disassembled easily. However, these holes on the structure experience tensile stresses on the surface which subsequently will lead to fatigue failure. In order to increase the fatigue life of the material, cold expansion of rivet/fastener holes has been used for over four decades in the aircraft industry and it is very efficient approach to extend the fatigue life of the aircraft structure [1-3]. Today, two common cold expansion methods employed are roller burnishing technique and split-sleeve method.

Roller burnishing technique consists of a tapered mandrel and pin roller bearing held in a cage. The tapered mandrel is inserted into the hole and it is pulled through the roller bearing cage which will induce the compressive residual stress around the hole [4]. However, the split sleeve cold expansion method, in which a tapered mandrel fitted with lubricated split sleeve is pulled through a hole, is considered as the most effective way in creating beneficial compressive residual stress around expanded holes since compressive residual stress remains tangential to the hole edge as the mandrel is being removed from the hole [4]. The development of compressive residual stress around the holes due to the plastic deformation of the material enhances the fatigue life of fastener joints since the initiation of fatigue cracks at the stress concentration region is delayed. The role of split sleeve is to ensure the correct radial expansion of the hole and prevent damage to the hole by avoiding the direct



contact between the sliding mandrel and the hole. Figure 1 shows the schematic diagram of the split sleeve cold expansion method.

Residual stress is the stress that exists in a body due to many conditions such as material properties, expansion ratio, thickness of the material, size of the hole and others. Odzemir and Herman [4] indicated that the compressive residual hoop stresses became increasingly compressive as the plate thickness increases for a given degree of expansion. The same goes to the research done by Nigrelli and Pasta [6] where the results showed that the hoop residual stress increased as the plate thickness was increased from 3 mm to 10 mm. In this research, the residual stress induced by split-sleeve cold-expansion process was simulated using finite element analysis. Gopalakrishna et al. [7] have proved that residual stress increases with the increase of expansion ratio until 5% and then decreased for 6% expansion. Rahman Seifi [8] applied cold expansion process to a plate made from elastic-perfectly plastic material. Residual stresses distributions were obtained by analytical and numerical method (using FEA method). The results showed that the stresses due to external loading were influenced by residual stresses. The maximum stresses found in the plate were observed to have been reduced by about 46%.

Most of the research done previously only focused on one factor at a time that can affect the residual stress distribution. However, in this work two factors that affect residual stress distribution, namely the expansion ratio and plate thickness were considered. This study is related to the previous work done by Karuppanan et al. [9] where the thickness and the centre distance between the holes were varied. They proved that the compressive residual stresses increased as the plate thickness increased. They also found that the residual stresses at the entrance face and the exit face were less compressive than the residual stresses at the mid-thickness of the plate.

In this study, the expansion ratio of the plate were varied from 1% to 6% and the diameter of the hole was kept constant with the centre distance between holes (c/d) ratio was fixed at 2. In addition, the thickness was varied according to the ratio between the thickness and the hole diameter (t/d) of 1, 2 and 3. Aluminium alloy 7475-T61 was used as the material for the model developed using ANSYS.

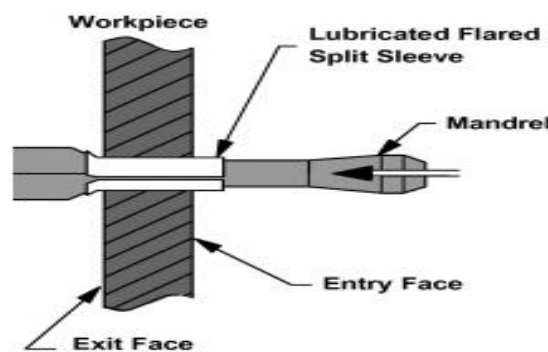


Figure 1. The schematic of the split sleeve cold expansion process [5].

2. Methodology

Figure 2 shows the plate model considered in this study. It consists of a plate containing two holes each with diameter, $d = 5$ mm with a centre distance between the holes, $c = 10$ mm. The dimensions of the plate were: width $w = 50$ mm, height $h = 50$ mm, and thickness over diameter ratio $t/d = 1, 2$ and 3 . The expansion ratio of 1% to 6% was considered.

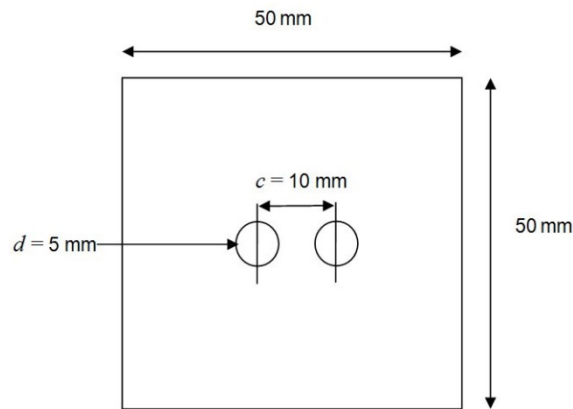


Figure 2. Dimension of the model.

However, only one quarter of the plate was modelled for the analysis since simultaneous hole expansion was considered. Figure 3 shows one quarter of the plate which was modelled in ANSYS where the stresses were measured from point *B* to point *A*. The dimensions used were: width $w = 25$ mm, height $h = 25$ mm and hole diameter $d = 5$ mm, as shown in Figure 3. Based on the research done by Papanikos and Meguid [1], the simultaneous expansion will result in higher compressive residual stresses compared with sequential expansion where half of the plate is modelled.

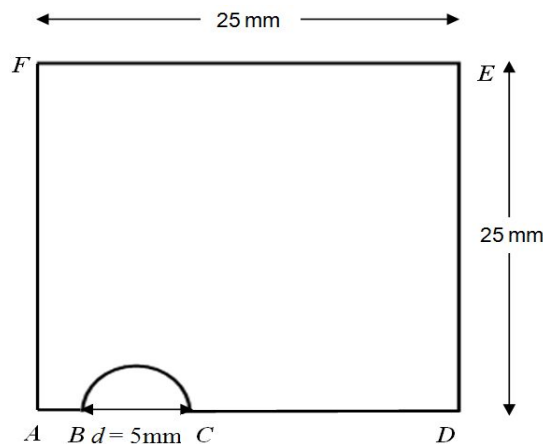


Figure 3. One quarter of the plate

Table 1 shows the material properties used in the model. These data were required to define the material in ANSYS.

Table 1. Mechanical properties of 7475-T61 Aluminium alloy [10].

Mechanical Properties	Unit
Yield Strength, σ_y	490 MPa
Ultimate Tensile Strength, σ_{UTS}	565 MPa
Modulus of Elasticity, E	70.3 GPa
Poisson's Ratio, ν	0.33

Figure 4 shows the stress versus strain curve for Aluminium 7475-T61 alloy. This curve is required to define the elastic and inelastic properties of this material.

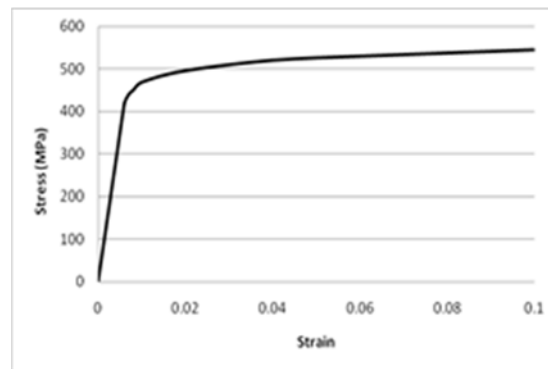


Figure 4. Stress versus strain curve for Aluminium 7475 alloy [5].

The element type considered for the model created in ANSYS was SOLID185. This type of element has plasticity, creep, stress stiffening, large deflection and large strain capabilities. Figure 5 shows the meshed model with fixed and symmetric boundary conditions. The symmetric boundary conditions were imposed on the side surfaces along the edges AB, CD, and AF as shown in Figure 5. Side surfaces along edges DE and EF were considered as the fixed boundary condition. The inner surface of the hole was then subjected to incremental pressure loading since the tapered mandrel was considered in this study.

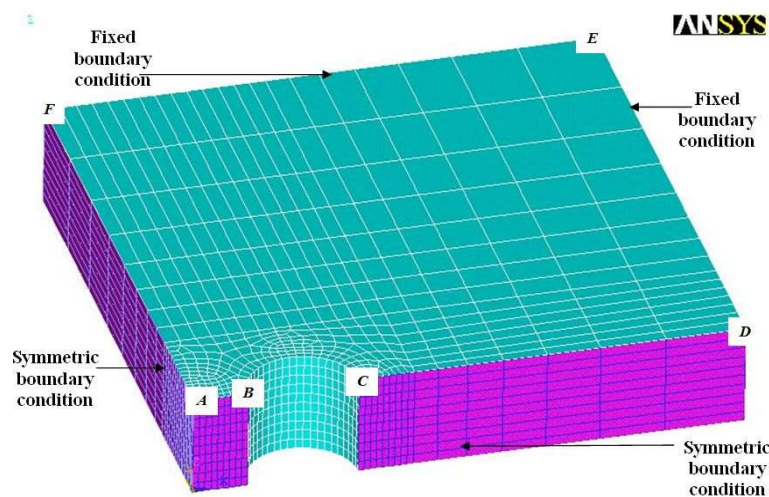


Figure 5. Meshed model with fixed and symmetric boundary conditions.

3. Results and Discussion

3.1. Validation

The experimental result from the study by Odzemir and Hermann [4] was used for the validation. Odzemir and Hermann [4] used 5 mm thick Aluminium 7050-T76 alloy plate with the size of 300 x 40 mm in their experiment. A hole was drilled at the centre of the plate and the hole was expanded using Fatigue Technology Incorporation (FTI) method with the different percentage of expansion, 2%, 4% and 6%. For validation, a quarter of the model was considered for modelling in ANSYS. Using this model, the stress distribution in x-axis and y-axis can be analysed at the edge of the model by plotting the results of the nodes. Figure 6 shows the model of the plate for validation which was developed in ANSYS.

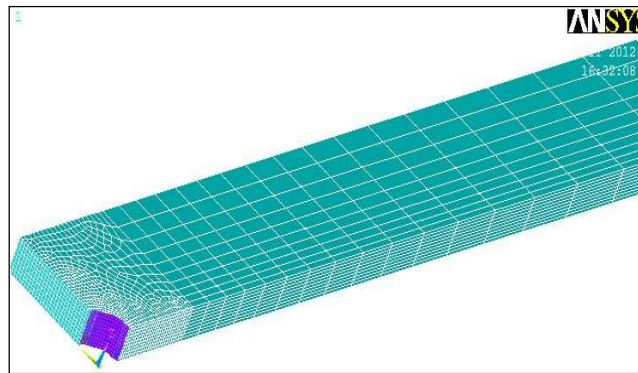


Figure 6. The 3D model of the plate for validation which was developed in ANSYS.

Experimental study done by Odzemir and Hermann showed that, 4% FTI expansion results the most compressive residual hoop stress compared with 2% and 6 % FTI expansion. The same goes to the finite element analysis done by the authors, where 4% expansion showed the most compressive residual stress compared with 2% and 6% expansion.

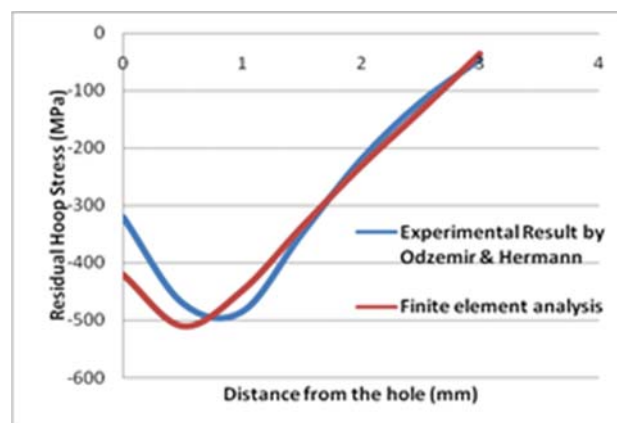


Figure 7. Comparison of residual stress developed in Aluminium 7050 T76 at 4% expansion using finite element analysis and experiment done by Odzemir & Hermann.

Figure 7 shows the comparison of residual stress results in 5 mm thickness Aluminium 7050-T76 at 4% expansion between finite element analysis and experiment conducted by Odzemir and Hermann. Based on the graphs, the residual stress developed at the edge of the hole using finite element analysis was slightly higher compared with the residual stress at the edge of the hole developed in experiment conducted by Odzemir and Hermann. In experiment done by Odzemir and Hermann, the lower value of compressive residual stress at the edge of the hole in that experiment was caused by the shear stress and frictional force due to the axial movement of the mandrel. In finite element analysis, the value of shear stress and frictional force were neglected since the lubricated split sleeve was considered in this study. Nigrelli and Pasta [6] stated that the low residual stress may be caused by the shear stress from the axial movement of the mandrel. This is the reason why the compressive residual stress at the edge of the hole in experiment done by Odzemir and Hermann was lower compared with the residual stress at the edge of the hole developed in finite element analysis done by the authors. However, the highest values of compressive residual stress developed by these two methods were almost the same which was about -500 MPa and the shape of the graphs was almost the same after this value. Therefore, the finite element analysis done was considered valid and this method of analysis can be used for this study.

3.2. Finite Element Analysis

In order to investigate the effect of thickness and expansion ratio on the residual stress distribution, finite element modelling was executed. The t/d ratios of 1, 2 and 3 were considered. Figure 8 shows the model of the 3-D finite element modelling using ANSYS with 4% cold expansion ratio for $t/d = 2$. The expansion ratios were varied from 1% up to 6% for each plate thickness.

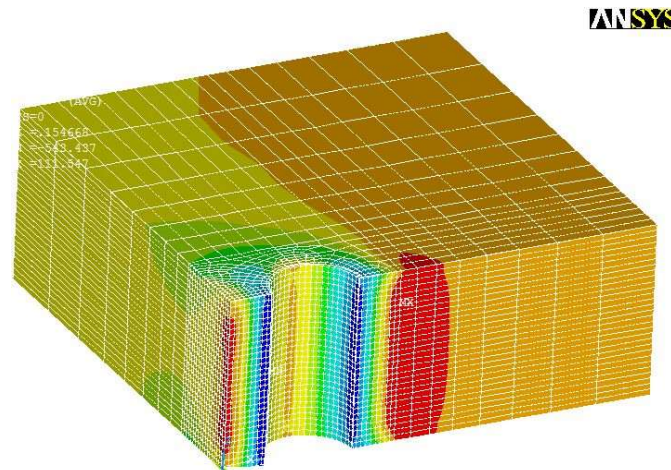


Figure 8. Model for $t/d = 2$ with expansion ratio = 4%.

3.2.1. Effect of plate thickness on residual stress. Odzemir and Hermann [4] noticed that the change in plate thickness can result in different values of residual stress around the cold expanded hole. Therefore, this effect has been investigated by evaluating the residual stress near the expanded hole for three different values of plate thickness. Residual stress in Y-direction was considered in this study and this stress is known as the tangential residual stress. The tangential residual stress is relevant in this study because the compressive residual stresses remain tangential to the hole edge as the mandrel is removed from the hole after the application of the load. The value of tangential residual stress is also higher compared with radial residual stress. These residual stresses were analysed on the surface of the plate starting from point B to point A as shown in the Figure 3. It is important to know the residual stress behaviour on the surface of the plate because the fatigue process initiates the crack at the surface of the plate due to excessive load. Figure 9 shows the stress behaviour around the expanded hole due to the different t/d for a fixed expansion ratio.

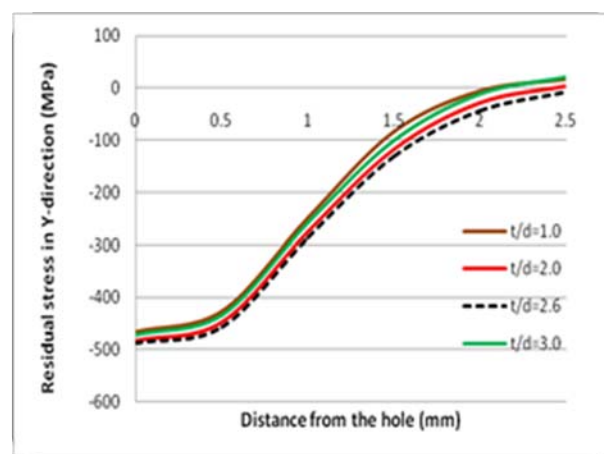


Figure 9. Residual stresses graph versus distance from the hole for 4% expansion ratio.

Based on the graphs shown in Figure 9, we can observe that the residual stress becoming more compressive for $t/d = 2$ as compared with $t/d = 1$ and become less compressive for $t/d = 3$. From here, different plate thickness between $t/d = 2$ and $t/d = 3$ was used to find the optimum thickness to induce high compressive residual stress. $t/d = 2.6$ showed the highest compressive residual stress as the plate thickness was varied between $t/d = 2$ and $t/d = 3$. From the graphs, the maximum compressive stress was found close to the hole edge and then the compressive residual stress values decreased rapidly away from the edge of the hole. The residual stress become more compressive as the thickness is increased from 5 mm to 13 mm due to the change in the state of stress from the plane-stress to the plane strain condition. 13 mm plate thickness or $t/d = 2.6$ is considered as the optimum plate thickness to induce high compressive residual stress in this project and further thickness increment will cause the residual stress to become less compressive. The less compressive residual stress is due to the blocking action of plastic zone. Plastic zone is important in creating the residual compressive stress and due to blocking action of plastic zone, further thickness increment after $t/d = 2.6$ will reduce the value of residual compressive stress.

3.2.2 Effect of expansion ratio on residual stress. Figure 10 shows the stress behaviour around the expanded hole due to the different expansion ratio.

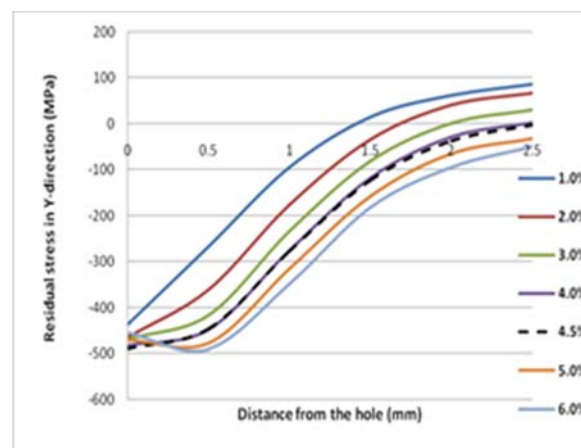


Figure 10. Residual stresses graph versus distance from the hole for $t/d = 2$.

Based on the graphs shown in Figure 10, the stress at edge of the hole becomes more compressive as the expansion ratio is increased up to 4 % and it become less compressive for further level of expansion for $t/d = 1$, $t/d = 2$ and $t/d = 3$. From here, different expansion ratio between 4% and 5% was applied at the hole to find the optimum expansion ratio to induce high compressive residual stress at the edge of the hole. 4.5 % expansion ratio showed the most compressive residual stress at the edge of the hole as the expansion ratio of the hole was varied between 4% and 5%. However, the area of the compressive part increases as the degree of expansion increases. This is due to the increase of applied load at the hole that will deform the material beyond the yield point and extends the plastic zone to a larger area. Plastic zone size is a critical factor in creating compressive stress. 4.5% of expansion ratio was considered as the optimum level of cold expansion and due to reverse yielding, residual compressive stresses at the edge of the hole become relaxed. Therefore, as the degree of expansion increases beyond 4.5%, the higher reverse yielding resulted in less compressive residual stresses at the edge of the hole. Reverse yielding is a condition that occurs when the stress in a material is decreased or relieved when the material is subjected to prolonged constant strain [11]. Expanding the hole beyond the limit only intensifies the stress relaxation at the edge of the hole which will reduce the compressive residual stress at the edge of the hole.

Expansion ratio of 4.5% with $t/d = 2.6$ are considered as the best condition to induce the high compressive residual stress which will reduce the propagation of fatigue cracks on the surface of fastened structure. Figure 11 shows the residual stress developed in optimum condition.

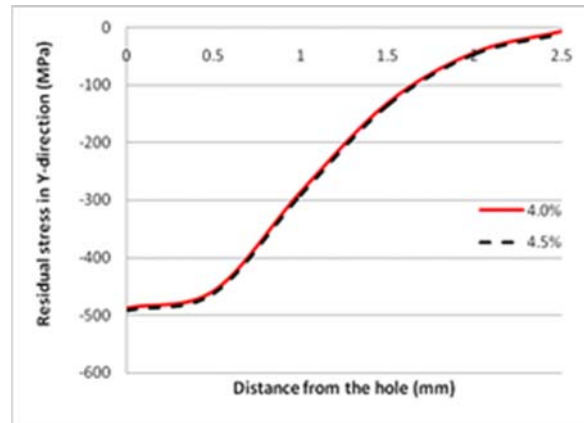


Figure 11. Residual stresses graph versus distance from the hole for $t/d = 2.6$ at 4% and 4.5% expansion ratio.

Based on the graph shown in Figure 11, we can observe that the residual stress becoming more compressive at 4.5% expansion ratio as compared with 4% expansion ratio for $t/d = 2.6$. This is the reason why $t/d = 2.6$ with 4.5% expansion ratio are considered as the best condition to induce the high compressive residual stress.

3.2.3 Stress analysis at different through-thickness position. Figure 12 shows the residual stresses through the thickness at the edge of the hole from entrance face ($z = 0$ mm) up to the exit ($z = 10$ mm) with different expansion ratios.

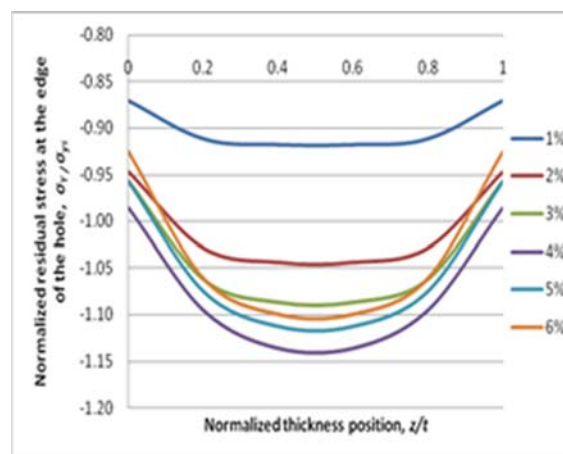


Figure 12. Residual stress at different through-thickness position with different expansion ratios for $t/d = 2$.

Based on the graphs, the compressive residual stresses near the entrance and the exit face are lower than the stresses on the mid-thickness for all expansion ratios. The presence of this less compressive residual stress near the entrance and exit face may be caused by the shear stress due to the axial movement of the mandrel. The graphs also show that the residual stress becomes more compressive as the expansion ratio is increased up to 4% expansion and it becomes less compressive for further level

of expansion. As discussed before, the residual stress become more compressive due to the increment of plastic zone and it started to decrease beyond 4% expansion due to reverse yielding. The same behaviour of residual stress distribution was observed for other plate thickness where the compressive residual stresses start to decrease beyond 4% expansion ratio.

4. Conclusions

The effect of plate thickness and expansion ratio toward residual stress distribution around the cold expanded hole has been analysed using ANSYS on 7475-T61 plates. The failure of a component due to excessive tensile residual stress can be avoided by applying the findings in this study.

From the results, we conclude that the residual stress become more compressive as the plate thickness is increased up to $t/d = 2.6$ due to the change of the state of stress from plane-stress to plane strain and it starts to decrease for further level of thickness due to blocking action of plastic zone. Furthermore, $t/d = 2.6$ was considered as the optimum plate thickness to induce high compressive residual stress in this study.

The residual stress at edge of the hole becomes more compressive as the expansion ratio is increased up to 4.5% and decreased for further level of expansion. However, as the degree of expansion increases, the area of the compressive part also increases. The residual stresses distributions at the edge of the hole are controlled by the degree of reverse yielding when it reaches the optimum level of cold expansion.

Therefore, 4.5 % expansion ratio with $t/d = 2.6$ were considered as the best relation to induce high compressive residual stress which will reduce the propagation of fatigue cracks on the surface of fastened structure. This study also found that the residual stresses near the entrance and the exit face are less compressive than the residual stresses on the mid-thickness of the plate.

Acknowledgment

The authors would like to thank Universiti Teknologi PETRONAS for providing the facilities for the research work.

References

- [1] Papanikos, P. and Meguid, S.A., 1998. Three-dimensional finite element analysis of cold expansion of adjacent holes, *International Journal of Mechanical Science*, **40**(10), 1019-1028.
- [2] Yucan F., Ende G., Honghua S., Jiuhua X. and Renzheng L., 2015. Cold expansion technology of connection holes in aircraft structures: A review and prospect, *Chinese Journal of Aeronautics*, **28** (4), 961-973.
- [3] Moreira P. M. G. P., De Matos P. F. P., Pinho S. T., Pastrama S. D., Camanho P. P., De Castro P. M. S. T., 2004. *Fatigue & Fracture of Engineering Materials & Structures*, **27** (9), 879-886.
- [4] Odzemir, T. and Hermann, R., 1999. Effect of expansion technique and plate thickness on near-hole residual stresses and fatigue life of cold expanded holes, *Journal of Materials Science*, **34**, 1243-1252.
- [5] Burlat, M., Jullien, D., Levesque, M., Bui-Quoc, T. and Bernard, M., 2008. Effect of local cold working on the fatigue life of 7475-T7351 aluminium alloy hole specimens, *Engineering Fracture Mechanics*, **75** (8), 2042-2061.
- [6] Nigrelli, V. and Pasta, S., 2008. Finite-element simulation of residual stress induced by split-sleeve cold expansion process of holes, *Journal of Materials Processing Technology*, **205**, 290-296.
- [7] Gopalakrishna, H.D., Narasimha Murthy, H.N., Krishna, M., Vinod, M. S. and Suresh, A.V., 2009. Cold expansion of holes and resulting fatigue life enhancement and residual stress in Al 2024 T3 alloy, *Engineering Failure Analysis*, **17**, 361-368.

- [8] Gomez, J. A., Lek, D., Song, I-H. and You, H. B., 2014. Study on stress evolution in the cooling process of micro hot embossing, *International Journal of Mechanical and Materials Engineering*, **9(20)**, 6 pages.
- [9] Karuppanan, S., Hashim, M. H. and Wahab, A.A., 2013. Finite Element Simulation of Residual Stresses in Cold-Expanded Plate, *Asian Journal of Scientific Research*, **6(3)**, 518–527.
- [10] Holt, J. M., Mindlin, H. and Ho, C. Y., 1996. *Structural Alloys Handbook*, West Lafayette, Indiana: CINDAS/Purdue University.
- [11] Rees, D.W.A., 2007. Descriptions of Reversed Yielding in Bending, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, **221(9)**, 981-991.