Effect of Drill on Mechanical and Modal Characteristics of Aluminum Sheet

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***Abstract*—This research paper presents a comparative numerical analysis to study the effect of drilling a center hole in an aluminum sheet on the static loading, linear buckling and modal characteristics of the sheet and compare it with a same sheet with no drill in it under the same boundary conditions. ANSYS workbench 15 was used to perform the analysis by using its static structural, linear buckling and modal modules on an Aluminum alloy (AA2024-T3) sheet. For analysis of drill geometry, Four models namely a neat sheet without drill, a sheet with circular drill, a sheet with triangular drill and a sheet with square drill were also developed. All drilled models had the same drill area and were subjected to the same loading conditions as the neat sheet. An overall reduction in mechanical and vibrational characteristic of the drilled sheet was observed as compared to its neat counterpart which was reflected by a 70%increase in the maximum generated stress and an 11% increase in the corresponding deformation along with the reduction in buckling load multipliers and modal natural frequencies. It was observed that the stress generated in the metallic sheet with a center drill was directly proportional to the number of stress risers even if the drill area was same. A 68% increase in stress generated for circular, 71% for triangular and 76% for square drill was observed compared to the neat sample. The maximum stress was generated on the stress risers perpendicular to the loading direction.**

***Index Terms*— Aluminum Alloys, ANSYS, Finite Element Analysis, Stress Concentration**

I. Introduction

Metallic materials are one of the oldest and most popular class of materials known to mankind. Their low cost, ease of extraction and diverse range of mechanical, electrical, thermal and corrosion characteristics have signified their usage in automotive, aerospace, manufacturing and many other industries [1-14]. Their sheet forming properties have diverse structural applications so different machining techniques are applied on these metallic sheets. Drilling is a common machining operation used in the manufacturing industry to generate a hole in the part for joining or assembly purpose. Generally circular drills are used but as per requirement the drill can be of any desired shape. Different shapes of drills can result in different types of stresses in the part when loaded [15-19].

Machining of metals is an important part of any manufacturing facility. Many complex metallic structures are made by common machining techniques such as drilling, milling, facing and knurling operations. In engineering design, it is significant to consider the effects of machining on the properties of the material and part being machined since cuts and drills create sites for stress concentration which can later change the mechanical behavior of the machined part. Aluminum sheets are an important component in automobile and aerospace industries where high precision machining is done on daily basis to manufacture automotive and aircraft structures due to their exceptional corrosion resistance, low cost, high specific strength and good machinability[2, 7, 20, 21].

Finite Element Analysis (FEA) is a growing engineering practice that computes engineering solution using model generation, division of model into small finite elements called meshes and solving that model under applied boundary conditions to give an approximated solution referred as numerical solution. ANSYS, ABAQUS and Solid Works are common commercial FEA software. Static structural analysis in FEA refers to loading a model under a static load and analyzing the generated stress distributions and deformations for both principal and directional values. Linear buckling modules are used to study different modes for a structure to deform and buckle under the compressive forces which lie in the linear elastic region i.e., they do not plastically deform the part. Modal analysis module is used to study the modes and natural frequencies of a mounted structure under various frequency ranges[22]. It is a simulation-based approach to design and solve engineering problems for fast and cost-effective engineering solutions. It is used to design and model parts or components, which are simulated using required conditions to visualize and simulate their behavior. This approach helps in faster iterations which enable the engineers to converge and optimize solutions efficiently and in less time [23-28].

This research has used FEA software ANSYS modules to study, how the behavior of an AA2024 sheet changes when a hole is introduced using static loading, linear buckling and modal analysis [15, 23, 25, 28-30]. Four models of the sheet, in which three of the models had a circular, a triangular and a square shaped drill of the same area, while the fourth sheet had

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no drill were developed. All these drilled models were subjected to the same loading conditions to study how the generated stress varied and were compared with the sheet having no drill.

II. Experimental Procedure

In order to study the effect of drill on the mechanical and modal behavior of the aluminum sheet, two models were generated in the design modeler option of ANSYS as per the material properties and dimensional specifications mentioned in TABLE I and TABLE II respectively.

TABLE I
Properties of AA2024-T3 [29, 31-33]

Property	Value
Density	2.78 g/cm^3
Young's Modulus	73100 MPa
Poisson's Ratio	0.33
Bulk Modulus	71667MPa
Shear Modulus	27481 MPa
Tensile Yield Strength	345 MPa
Ultimate Tensile Strength	483 MPa

TABLE II
Sheet Dimensions

Dimensions	Value (mm)
Length	50
Width	50
Thickness	3
Drill diameter	10

The model without drill was labelled as "Neat" and the model containing a center-drilled circular hole was labelled as "Drilled". The CAD model of both neat and drilled specimens are shown in Fig 1(a) and Fig 1 (b) respectively. The models were meshed using solid elements as shown in Fig 1 (c) and Fig 1 (d) respectively.

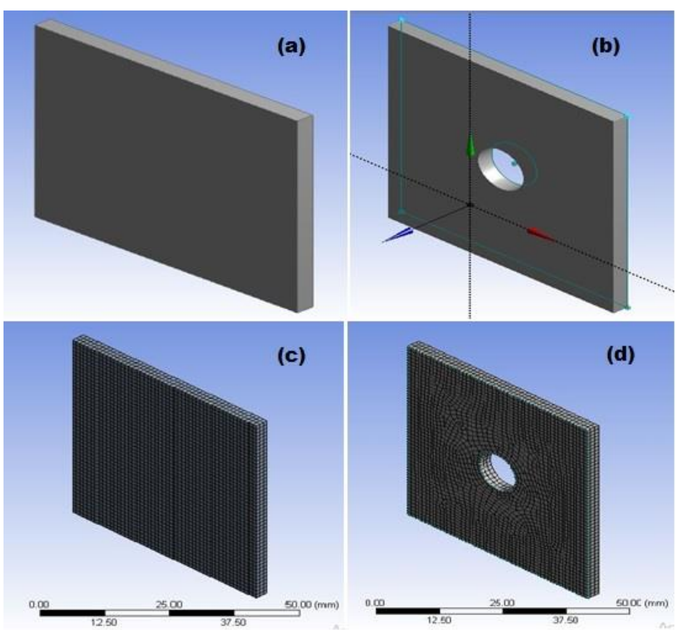

Fig 1: (a) CAD model of neat sheet, (b) CAD model of Drilled sheet, (c) Meshed Neat sheet, (d) Meshed Drilled sheet

The meshing statistics are provided in TABLE III. To compare the mechanical behavior of the models the static structural module was used, and both the models were loaded uniformly along the X-axis by subjecting the sides to a 100 N force as per the conditions shown in Fig 2(a). To study the buckling behavior of the models, the linear buckling module was used and both the models were subjected to the boundary conditions shown in Fig 2(b) in which one side along the X-axis was subjected to a fixed support while the opposite side was subjected to a uniform compressive force of 100 N with number of modes to be evaluated were set to 6. In case of vibrational frequency response, modal analysis of both the models was performed by mounting them along the X-axis as show Fig 2(c) and number of modes to be evaluated were set to 6. The static loading conditions for drill geometry are shown in Fig 2(d).

TABLE III
Meshing Statistics

Specimen	Mesh type	No. of Nodes	No. of Elements
Neat	Solid	37100	7203
Drilled	Solid	35829	6915

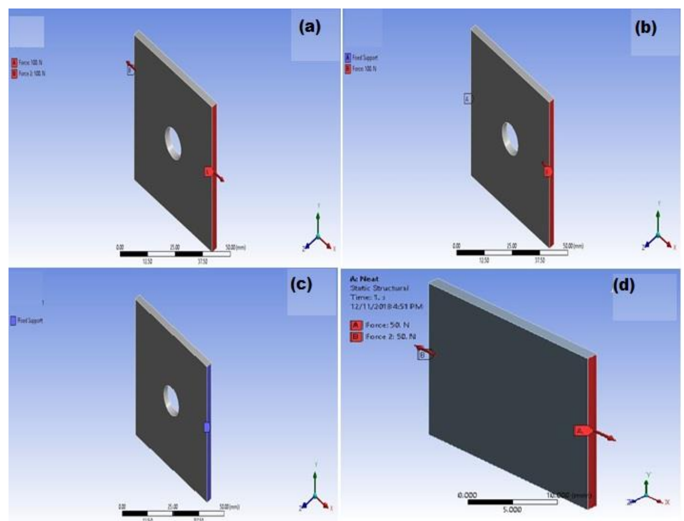

Fig 2: (a) Static Loading conditions, (b) Loading Conditions for buckling analysis, (c) Mounting Conditions for Modal analysis, (d) Static loading conditions for drill geometry

In order to study the effect of drill geometry, the first step was to generate the finite element models for the comparative study bearing the desired drill geometries. For that, the base metal was to be defined in the engineering data module of the ANSYS software. The metal used was an aluminum alloy and the defined properties are tabulated in TABLE I. The sheet without any drill was designed using the ANSYS Design modeler as per the dimensions shown in TABLE IV. This sheet will now be referred to as "Neat" sheet. The next step was to generate a duplicate model of the neat sheet and drill the hole of specified diameter. This model was labeled as "Circle". The third model was generated by extruding an equilateral triangular hole through the center of the neat sheet and the model was labelled as "Triangle". The fourth model was developed by extruding a square through the center of the sheet and the model was labelled as "Square". For comparative study it was decided that the triangular and square shaped drills would have the same area as that of the circular drill. The corners of these drills would be distributed such that each side of the sheet is exposed to only one sharp corner at a time and since the sheet has four sides, the maximum corners introduced in the drills was four.

TABLE IV
Sheet Dimensions

Dimensions	Value (mm)
Length	25
Width	25
Thickness	1.5
Drill diameter	5
Triangle side length	6.733
Square side length	4.430

TABLE V
Meshing Statistics

Model	Mesh type	No. of Nodes	No. of Elements
Neat	Solid	10600	5377
Circular		4619	2467
Triangle		4335	2269
Square		4974	2654

The areas of circle, triangle and square were calculated using equations (1), (2), (3) respectively and thus the respective side lengths of square and triangle were specified in TABLE IV [21, 22].

$$A = \pi r^2 \quad (1)$$

$$A = \sqrt{3}/4\ a^2 \quad (2)$$

$$A = a^2 \quad (3)$$

The meshing of the models was done using sold elements and the drill surface was refined using mesh refinement module of the software, thus a triangular surface mesh was generated for the models as shown in Fig 3.

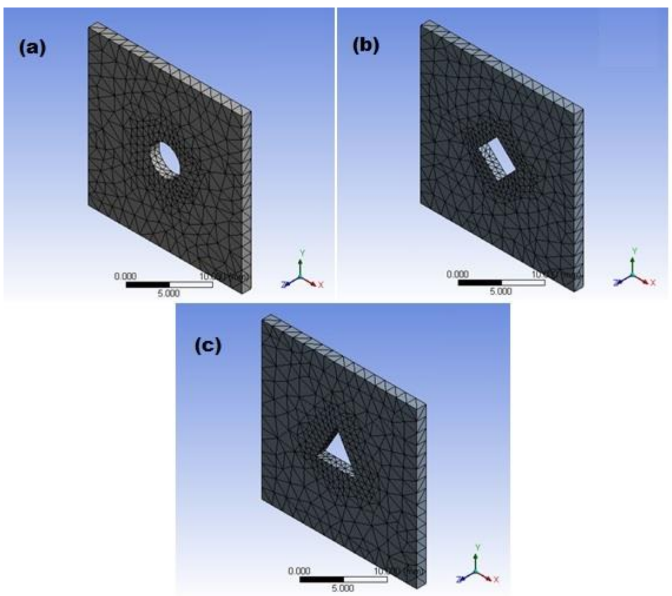

Fig 3: Meshed model (a) Circle, (b) Square, (c) Triangle

The corresponding number of nodes and elements are provided as meshing statistics in TABLE **V**. The loading conditions applied on the models is shown in Fig 2(d). Both end faces of the models along the X-axis were loaded with a uniform force of 50 N. The equivalent Von-mises stress was evaluated for all the models to compare their behavior. All the models were meshed, loaded, and analyzed using Static Structural Module of the software.

III. RESULTS AND DISCUSSIONS

The Von-mises stress distribution and deformation for the static loading of both the neat and drilled sheets are shown in Fig 4 and the results are tabulated in TABLE VI. It can be seen that not only the maximum stress and deformation in the drilled sheet is higher than the neat sheet, but also the stress is distributed uniformly along the cross-section of the neat sheet, while it is concentrated around the drilled region in the case of the drilled sheet. This can be attributed to the stress magnification phenomena in which due to the presence of a crack, i.e. the drills, there is a significant reduction in area of the specimen, leading to an increase in the generated stress under the same loading condition.

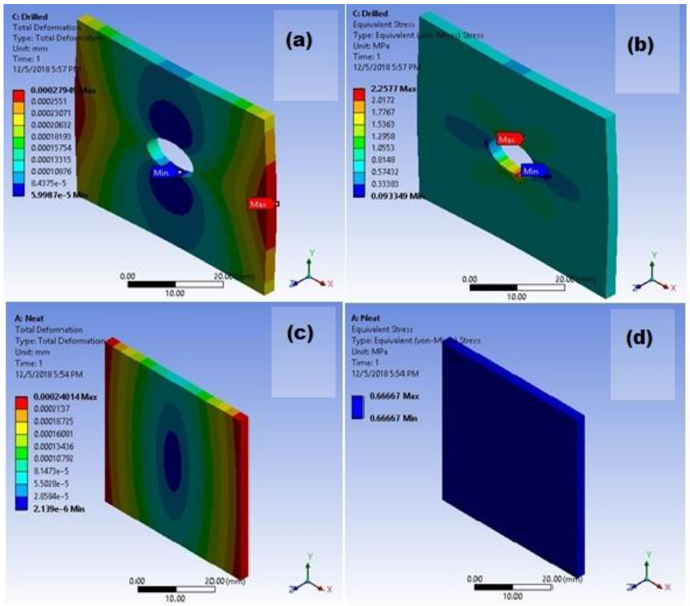

Fig 4 : (a) Total deformation in drilled sheet, (b) Von-mises stress distribution in drilled sheet, (c) Total deformation in neat sheet, (d) Von-mises stress distribution in neat sheet

The results of linear buckling analysis are tabulated in TABLE VI in terms of mode number and load multipliers while the mode shapes are shown in Fig 5 and Fig 6 for both the neat and the drilled sheets respectively. It can be seen that although the mode shapes are more or less similar for both the sheets, the values of load multiplier for each mode are less for the drilled sheet as compared to the values of neat sheet likely due to the increase in the generated stress. This indicates that under the same loading parameters, the drilled sheet is more likely to buckle at a lesser load than the neat specimens.

The modal analysis results of both the sheets are tabulated in TABLE VI and the corresponding mode shapes are shown in

Fig 7and Fig 8 respectively. A similar trend observed in the results of buckling analysis is also reflected here that mode shapes are similar for the neat and drilled sheets however, the tabulated results indicate a lower natural frequency of each mode of the drilled sheet as compared to its neat counterpart. This can be attributed to the reduction in mass of the drilled specimens, due to which they can resonate or fail under vibrations at a lower frequency than their neat counterparts.

TABLE VI
Results for Static, Buckling and Modal Analysis

Test Type	Parameter	Neat	Drilled
Static Loading	Maximum Von-Mises Stress (MPa)	0.67	2.25
	Maximum Deformation (mm)	0.00024	0.00027
Linear Buckling	Mode# / Load Multiplier	1/87.266	1/81.39
		2/611.64	2/560.59
		3/775.32	3/725.53
		4/1322.5	4/1205.7
		5/2135.5	5/1989.2
		6/2629.2	6/2450.2
Modal	Mode# / Frequency (Hz)	1/1041.1	1/1029.8
		2/2459.9	2/2394.6
		3/6241.8	3/6107.
		4/7921	4/7700.5
		5/8877.7	5/8821.9
		6/10727	6/10312

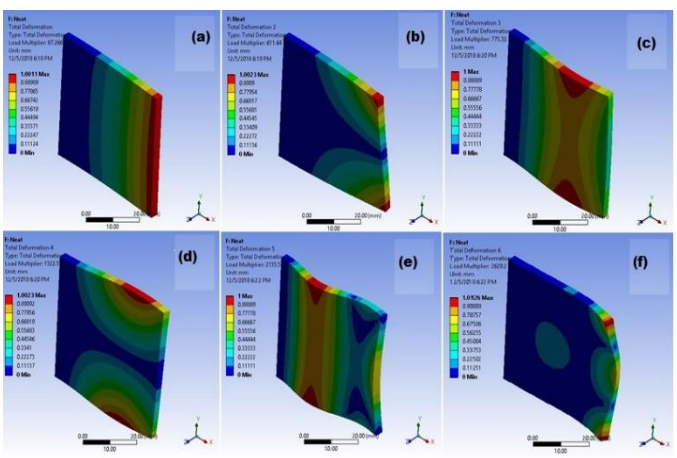

Fig 5 : Neat sheet buckling modes, (a) First, (b) Second, (c) Third, (d) Fourth, (e) Fifth, (f) Sixth

The stress distributions for the generated Von-Mises stress for all the models is shown in Fig 9, while the tabulated results for the same are shown in TABLE VII. It is evident from the results that in case of the neat model, the stress is uniformly distributed along the entire sheet while in the case of circular drill, the stress is concentrated around the drilled corners which are perpendicular to the direction of the force applied. In the case of the triangular drill, although the stress is concentrated at the three corners, the maximum value of the stress was observed on the corner perpendicular to the direction of the applied force.

In the case of the square drill, the stress is concentrated at the four corners, but the maximum stress was observed on the corners perpendicular to the loading direction.

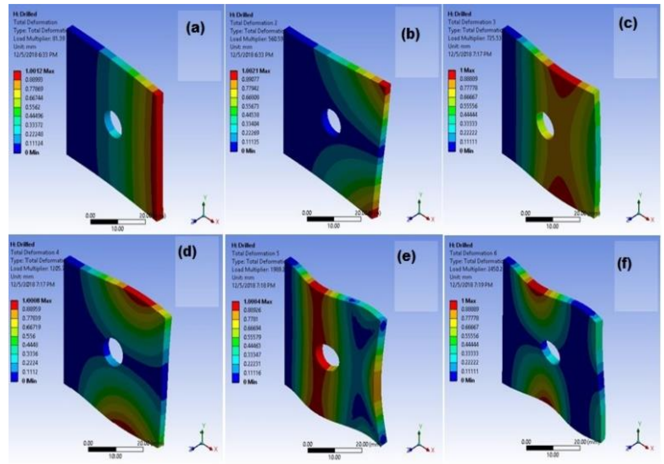

Fig 6 : Drilled sheet buckling modes, (a) First, (b) Second, (c) Third, (d) Fourth, (e) Fifth, (f) Sixth

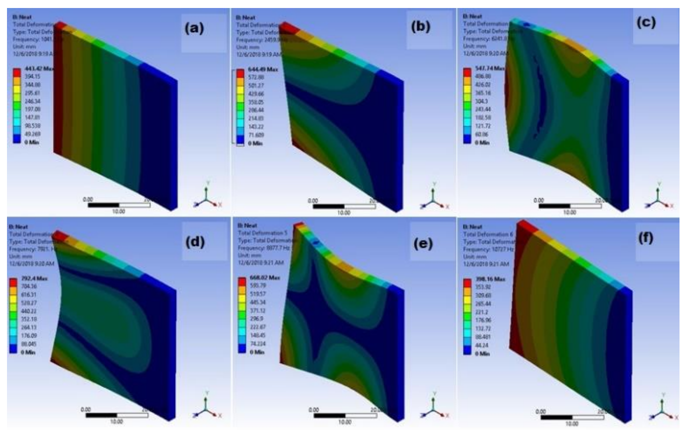

Fig 7 : Neat sheet mode shapes, (a) First, (b) Second, (c) Third, (d) Fourth, (e) Fifth, (f) Sixth

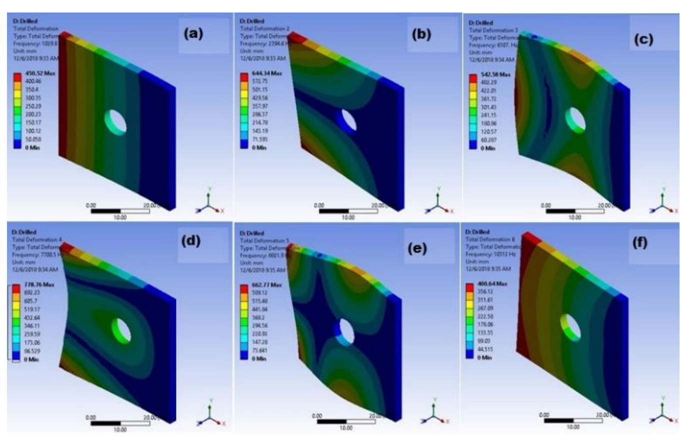

Fig 8 : Drilled sheet mode shapes, (a) First, (b) Second, (c) Third, (d) Fourth, (e) Fifth, (f) Sixth

Another interesting trend observed in the study was that the maximum stress generated in the sheets as compared with the neat model indicates that, as the drill geometry changed from circle to square, the number of sharp corners or stress risers increased from one in the case of circle, to three in the case of triangle and to a maximum of four in the case of square drill, which increased the value of the generated stress for the same area of drill as shown in TABLE VII and Fig 9.

TABLE VII
Results of Numerical Analysis for Drill Geometry

Model	Maximum Von-Mises Stress (MPa)
Neat	1.3333
Circle	4.1661
Triangle	4.6448
Square	5.7177

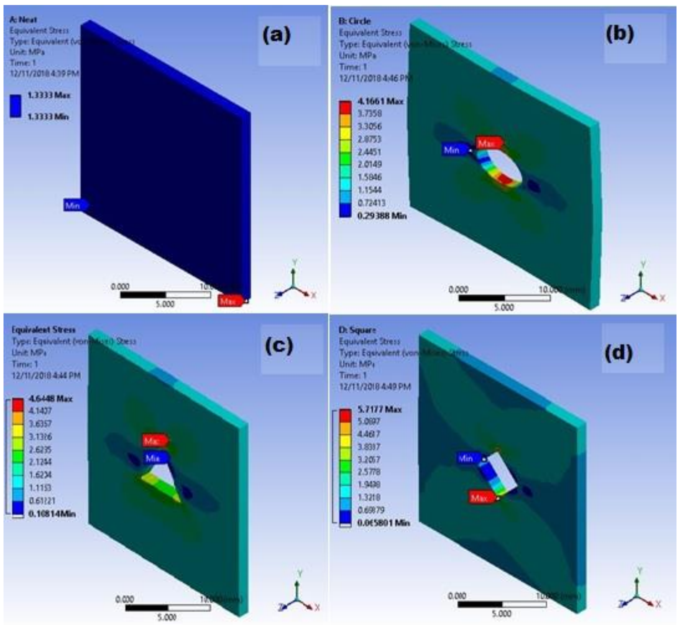

Fig 9 : Stress distributions (a) Neat model, (b) Circular hole, (c) Triangular hole (d) Square hole

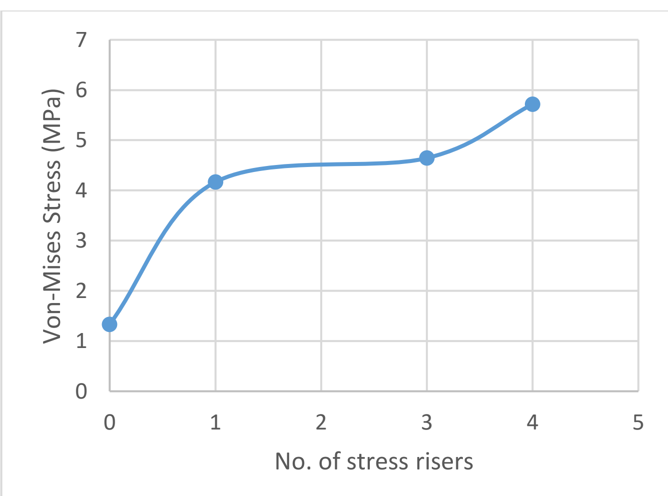

Fig 10 : Effect of stress risers on generated Von-Mises Stress

IV. Conclusion

The study results revealed the following few interesting facts and it is concluded by listing the same:

- Under the same static loading conditions, an increase of 70% in the maximum generated stress and an 11% increase in the corresponding deformation was observed for the drilled sheet as compared to the neat sheet.
- Reduction in load multipliers of the drilled sheet indicated that it will buckle at lower load as compared to the neat sheet.
- Reduction in the natural frequencies of the modal analysis for the drilled sheet indicated that it will fail at a lower frequency as compared to the neat sheet.
- Overall reduction for mechanical and modal characteristic was observed for the drilled sheet which can be tailored by redesigning and increasing the area of the sheet, reducing the drill diameter or by choosing a material of higher mechanical properties.
- The stress generated in a metallic sheet with a center drill is directly proportional to the number of stress risers at the same drilled area.
- 68% increase in stress generated for circle, 71% for triangle and 76% for square drill was observed compared to the neat sample.
- Circular drill generated the minimum stress, while the square drill of the same area generated the maximum stress comparatively.
- The maximum stress is generated on the stress risers perpendicular to the loading direction.
- ANSYS proved to be an effective analysis tool for the study since such high dimensional tolerances are difficult to fabricate and induce in a sheet in practice.
- From a designer's perspective, circular drills should be used for mechanical joining of sheets. However, where intentional failure is desired, square drills can be introduced.

References

[1] E. A. Starke and J. T. Staley, "Application of modern aluminum alloys to aircraft," *Progress in Aerospace Sciences*, vol. 32, pp. 131-172, 1996/01/01/ 1996.

[2] J. Hirsch, *Aluminium Alloys for Automotive Application* vol. 242, 1997.

[3] A. A. Khan, F. Ahmed, I. R. Memon, and X. Y. Ming, "Error Computations for Adaptive Finite Element Analysis," *Journal of Engineering and Applied Sciences (JEAS), University of Engineering and Technology, Peshawar*, vol. 21, 2002.

[4] H. J. Liu, H. Fujii, M. Maeda, and K. Nogi, "Tensile properties and fracture locations of friction-stir-welded joints of 2017-T351 aluminum alloy," *Journal of Materials Processing Technology*, vol. 142, pp. 692-696, 2003/12/10/ 2003.

[5] A. A. Khan and I. R. Memon, "Computation of Critical Crack Sizes for Crack Growth Prediction in Thin Plates," *J. Eng. Appl. Sci.(Peshawar),* vol. 23, pp. 71-77, 2004.

[6] Y. Rui, A. Subic, M. Takla, C. Wang, A. Niehoff, N. Hamann*, et al.*, *Biomimetic Design of Lightweight Vehicle Structures Based on Animal Bone Properties* vol. 633, 2013.

[7] I. Ahmed, S. Ullah, Z. S. Toor, A. Wadood, A. N. Butt, and S. W. Hussain, "Design, Fabrication and Beta testing of Four point Bend Immersion (FPBI) apparatus for the study of Stress Corrosion Cracking (SCC)," in *Student Research Paper Conference (SRPC) Institute of Space Technology (IST), Islamabad, Pakistan*, 2015, pp. 162-166.

[8] A. A. Khan, M. Ahmad, and M. A. Ashraf, "Residual Life Estimation of an Attach Angle for a Cargo Aircraft," *Journal of Failure Analysis and Prevention,* vol. 16, pp. 1126 - 1133, 2016.

[9] M. Tisza, D. Budai, P. Z. Kovács, and L. Zs, "Investigation of the formability of aluminium alloys at elevated temperatures," *IOP Conference Series: Materials Science and Engineering,* vol. 159, p. 012012, 2016.

[10] Z. S. Toor, "Applications of Aluminum-Matrix Composites in Satellite: A Review," *Journal of Space Technology (JST),* vol. 7, pp. 1-6, 2017.

[11] Z. S. Toor, I. Ahmed, S. Ullah, A. N. Butt, and S. W. Hussain, "Influence of Ageing time and Stress on Corrosion behavior of AA2024-T6 in saturated NaCl Solution," *Journal of Space Technology (JST),* vol. 8, pp. 38-44, 2018.

[12] R. Sabir, A. A. Khan, H. J. Hasham, and I. A. Khan, "Buckling Load Prediction in Ortho-Grid Plates for Aerospace Structures," *Journal of Failure Analysis and Prevention,* vol. 18, pp. 647-658, 2018.

[13] Z. S. Toor, "Space Applications of Composite Materials," *Journal of Space Technology (JST),* vol. 8, pp. 65-70, 2018.

[14] Z. S. Toor, "Lessons In Risk Reduction From A Dental Implant Manufacturer," *Quality Progress (QP),* vol. 54, pp. 14-21, 2021.

[15] R. C. Shah and A. S. Kobayashi, "Stress intensity factors for an elliptical crack approaching the surface of a semi-infinite solid," *International Journal of Fracture,* vol. 9, pp. 133-146, June 01 1973.

[16] L. Westfall, B. J. Diak, M. A. Singh, and S. Saimoto, "Dynamic Dislocation-Defect Analysis and SAXS Study of Nanovoid Formation in Aluminum Alloys," *Journal of Engineering Materials and Technology,* vol. 130, pp. 021011-021011-7, 2008.

[17] S. Hale. (2015). *Why Worry About Sharp Corners and Point Loads?* Available: https://caeai.com/blog/why-worry-about-sharp-corners-and-point-loads

[18] CORROSIONPEDIA. (2018). *Stress Concentration Factor (Kt)*. Available: https://www.corrosionpedia.com/definition/1035/stress-concentration-factor-kt

[19] B. McGinty. (2018). *Stress Concentrations at Holes*. Available: http://www.fracturemechanics.org/hole.html

[20] Z. S. Toor, "Influence of Crack Morphology and its distribution on Stress magnification of AA2024-T3," *Journal of Space Technology (JST),* vol. 10, pp. 50-57, 2020.

[21] Z. S. Toor, "Finite Element Method for Numerical Stress Analysis of Aluminum plate," *Journal of Space Technology (JST),* vol. 10, pp. 01-06, 2020.

[22] M. Shifa, F. Tariq, F. Khan, Z. S. Toor, and R. A. Baloch, "Towards light weight multifunctional hybrid composite housing for satellite electronics," *Materials Research Express,* vol. 6, p. 125629, 2020/01/17 2020.

[23] D. Ngo and A. C. Scordelis, "Finite Element Analysis of Reinforced Concrete Beams," *Journal Proceedings,* vol. 64, 3/1/1967 1967.

[24] J. Kang, W. S. Johnson, and D. A. Clark, "Three-Dimensional Finite Element Analysis of the Cold Expansion of Fastener Holes in Two Aluminum Alloys," *Journal of Engineering Materials and Technology,* vol. 124, pp. 140-145, 2002.

[25] L. Engineering. (2012). *What is Von Mises Stress ?* Available: http://www.learnengineering.org/2012/12/what-is-von-mises-stress.htmls

[26] V. Kuppast, *FINITE ELEMENT ANALYSIS OF ALUMINIUM ALLOYS FOR THEIR VIBRATION CHARACTERISTICS* vol. 03, 2014.

[27] R. D. Sulamet-Ariobimo, J. W. Soedarsono, T. Sukarnoto, A. Rustandi, Y. Mujalis, and D. Prayitno, "Tensile properties analysis of AA1100 aluminium and SS400 steel using different JIS tensile standard specimen," *Journal of Applied Research and Technology,* vol. 14, pp. 148-153, 2016/04/01/ 2016.

[28] M. K. Bhuarya, M. S. Rajput, and A. Gupta, "Finite Element Simulation of Impact on Metal Plate," *Procedia Engineering,* vol. 173, pp. 259-263, 2017/01/01/ 2017.

[29] Y. Chen, A. H. Clausen, O. S. Hopperstad, and M. Langseth, "Stress–strain behaviour of aluminium alloys at a wide range of strain rates," *International Journal of Solids and Structures,* vol. 46, pp. 3825-3835, 2009/10/15/ 2009.

[30] Z.-m. Bai, X. Wu, C.-l. Wu, and J.-x. Wang, "Quench propagation properties analysis of high-temperature superconductors using finite element method," *Physica C: Superconductivity,* vol. 436, pp. 99-102, 2006/04/15/ 2006.

[31] M. i. from. (2018). *1100 (Al99.0Cu, A91100) Aluminum*. Available: https://www.makeitfrom.com/material-properties/1100-Al99.0Cu-A91100-Aluminum/

[32] A. A. S. M. Inc. *Aluminum 2024-T3*.

[33] Metalmen. (2018). *Aluminum 1100 properties & products*. Available: https://www.metalmensales.com/Aluminum-1100-Properties.html