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Effect of material type, cutout shape and temperature on stress and deformation analyses of thin plates

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Abstract

In this numerical and statistical paper, the effect of material type, cutout shape and temperature on von Mises stress and total deformation analysis of plates was examined using numerical and statistical methods. Each plate was analyzed under clamped boundary conditions. The areas of the cutouts were taken equal. Numerical calculations were conducted by Taguchi L_8 orthogonal array with three control factors using finite element software ANSYS Workbench. Material type, cutout shape, and temperature of plates were selected as control factors. Effects and the optimum levels of control factors were identified using analysis of signal/noise ratio. Also, meaningful control factors were obtained using analysis of variance. According to results obtained from this study, stress and deformation of plates with cutouts in the form of circular shapes is smaller compared to plates with cutouts in the form of square shapes. Compared to magnesium alloy, aluminum alloy leads to an increase in stress and a decrease in deformation of plates due to temperature increase. In addition, the applied temperature increase provides an increase in the stress and deformation values of the plates. The strongest control factors on stress outcomes are found to be cutout shape with 79.09% effect, temperature with 9.76% effect, and material property with 5.78% effect, respectively. Significant control factors on deformation outputs are obtained as temperature with 56.87% effect, cutout shape with 32.46% effect, and material property with 8.86% effect, respectively. This numerical and statistical study can be used as a reference paper for experimental and numerical studies in the thermal field.

Keywords: Cutouts, Stress, Deformation, Plate, FEM

1. Introduction

Metal materials can be observed to increase stress and deformation due to temperature increase. This is related to the mechanical and expansion coefficient of the material. The purpose of thermal analysis is to examine the behavior of material subjected to thermal loading. Thermal analyzes are carried out in many areas of engineering. In this regard, scientists conduct many studies involving thermal analysis. Impact of square cutout on thermal stress of composite plates made of aluminum metal matrix using steel fibers was evaluated by finite element software ANSYS under simply supported boundary conditions and each plate had four layers [1]. Numerical thermal stress of plates was performed and finite element method was used to calculation [2]. Thermal stress of square plates made from metal materials for different boundary conditions was numerically calculated under thermal load and ANSYS and ABAQUS software were used to perform the analyses [3]. Thermal stress and deformation of plates made of functionally graded materials including Aluminum and Zirconia materials were performed and finite element model was utilized [4]. Thermal stress of hollow circular cylinders made of functionally graded materials were carried out [5]. Thermal stress characteristic of plates with circular cutouts was evaluated under temperature loading [6]. Thermal stress propagation around the different

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cutout shapes were discussed and analytical technique was utilized [7]. As can be seen from the literature review, there are many studies on thermal stress. In this study, influence of material type, cutout shape and temperature on von Mises stress and total deformation analysis of plates made of different metal materials was studied using numerical and statistical techniques.

2. Material and Method

Magnesium alloy and aluminum alloy were used as metal materials to model the plates in finite element software. Mechanical properties of materials were tabled in Table 1.

Table 1. Material properties [9]

Materials	Young's Modulus (GPa)	Poisson's Ratio	Coefficient of Thermal Expansion (1/°C)
Magnesium Alloy	45	0.35	$2.6x10^{-5}$
Aluminum Alloy	71	0.33	$2.3x10^{-5}$

To conduct the numerical analysis, Taguchi L8 orthogonal array with three control factors was utilized. Material type was selected as the first control factor with two levels such as magnesium alloy and aluminum alloy. Cutout shape was considered as the second control factor with two levels such as square shape and circular shape. Temperature value applied to the plates was assumed as the third control factor with two levels such as 100 °C and 150 °C. Control factors and their levels were given in Table 2.

Table 2. Control factors and levels

Control Factors	Symbol	Levels	
		Level 1	Level 2
Material Type	A	Magnesium Alloy	Aluminum Alloy
Cutouts Shape	B	Square Shape	Circular Shape
Temperature	C	100 °C	150 °C

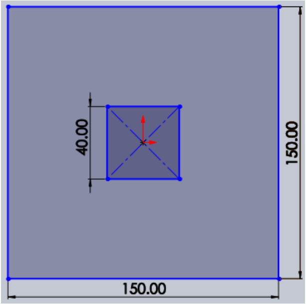
Aim of this study is to find the minimum stress and total deformation data of plate under different temperatures. To obtain the optimum results for von Mises stress and total deformation of plates based on the minimum responses, “smaller is better” quality characteristic in Taguchi method was used. The quality characteristic was given in Equation 1 [8].

$$\left(\frac{S}{N}\right)_{SB} \; for\; \alpha = -10.log\left(n^{-1}\sum_{i=1}^{n}(y)_i{}^2\right) \tag{1}$$

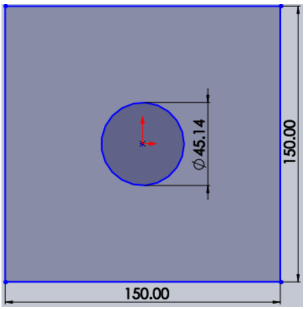
in which, n indicates the number of numerical analyses for finite element calculations in a trial and y_i defines i^{th} data evaluated. Also, meaningful control factors were obtained using analysis of variance at 95 % confidence level. All statistical analyzes and graphs related to statistical analyzes were performed using the Minitab R15 statistical software.

3. Finite Element Analysis

Numerical analyses were performed under static structure module in finite element software ANSYS Workbench (ANSYS Inc., USA) [9]. Von misses stress and total deformations for the minimum values were used as responses. Dimensions of plates was determined as 100 mm x 100 mm. Thickness was considered as 0.5 mm. Three-dimensional plates were designed using the SOLIDWORK drawing program. Plates were analyzed under clamped boundary conditions. Thermal condition was chosen as 100 °C and 150 °C. In other word, 100 °C and 150 °C temperatures were applied to plates. Mesh operation was carried out as program control. Element size was selected as 1 mm. The areas of the cutouts were taken equal. The cutout shapes were shown in Figure 1.



a)



b)

Fig. 1. Cutouts: a) square shape and b) circular shape

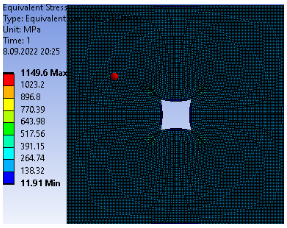
4. Results and Discussion

This numerical and statistical study deals with the examine of effect of material properties, cutout shape, and temperature on von mises stress and total deformation analysis of plates. Results for numerical and S/N data were tabulated in Table 3.

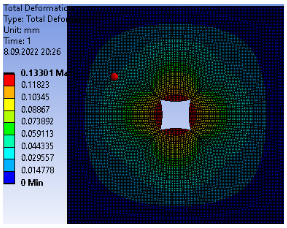
Table 3. Numerical data and S/N ratios

Test	Designation	Control Factors Material Type	Cutout Shape	Temperature	Results Stress σ, (MPa)	S/N η, (dB)	Deformation δ, (mm)	S/N η, (dB)
1	$A_1B_1C_1$	Magnesium Alloy	Square	100 °C	1149.60	-61.21094	0.13301	17.52231
2	$A_1B_1C_2$	Magnesium Alloy	Square	150 °C	1724.40	-64.73276	0.19951	14.00071
3	$A_1B_2C_1$	Magnesium Alloy	Circular	100 °C	315.96	-49.99264	0.09840	20.14001
4	$A_1B_2C_2$	Magnesium Alloy	Circular	150 °C	473.94	-53.51447	0.14760	16.61827
5	$A_2B_1C_1$	Aluminum Alloy	Square	100 °C	1568.50	-63.90969	0.11387	18.87181
6	$A_2B_1C_2$	Aluminum Alloy	Square	150 °C	2352.80	-67.43170	0.17081	15.34973
7	$A_2B_2C_1$	Aluminum Alloy	Circular	100 °C	430.19	-52.67321	0.08366	21.54923
8	$A_2B_2C_2$	Aluminum Alloy	Circular	150 °C	645.29	-56.19510	0.12550	18.02713
Overall Means					1082.59	-	0.13405	-

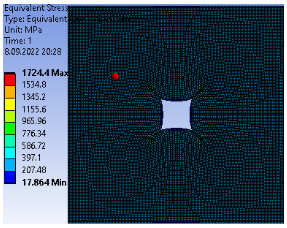
Finite element results for von Mises stress and total deformation analysis were visually illustrated in Figure 2. As can be seen from Figure 2, the maximum stress and deformation distributions were occurred around the cutout shapes.



1. Analysis for Stress



1. Analysis for deformation



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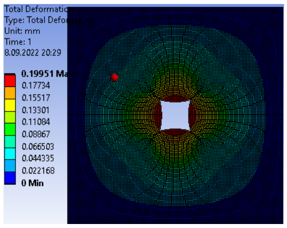
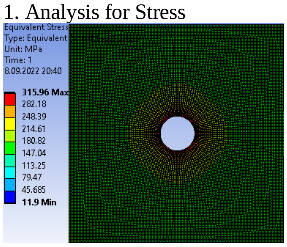


2. Analysis for deformation



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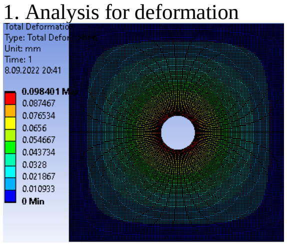

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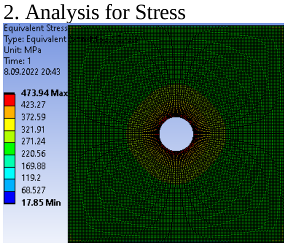
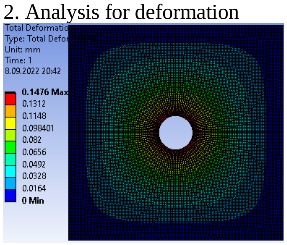
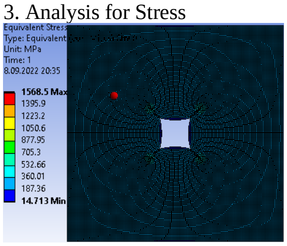


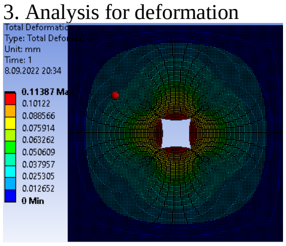
4. Analysis for Stress



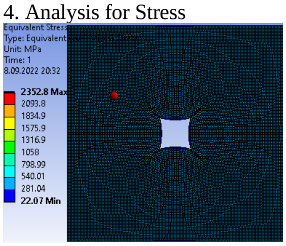
4. Analysis for deformation



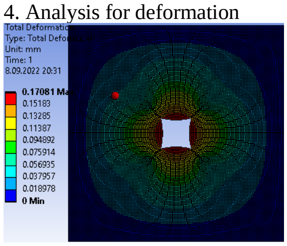
5. Analysis for Stress



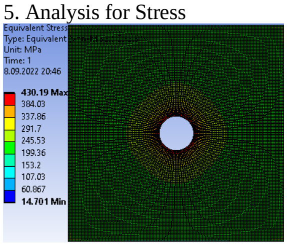
5. Analysis for deformation



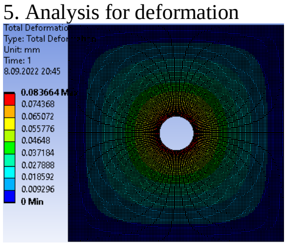
6. Analysis for Stress



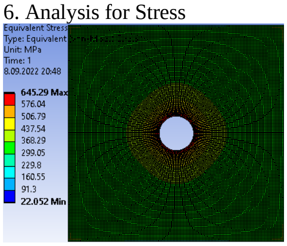
6. Analysis for deformation



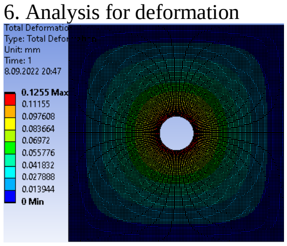
7. Analysis for Stress



7. Analysis for deformation



8. Analysis for Stress

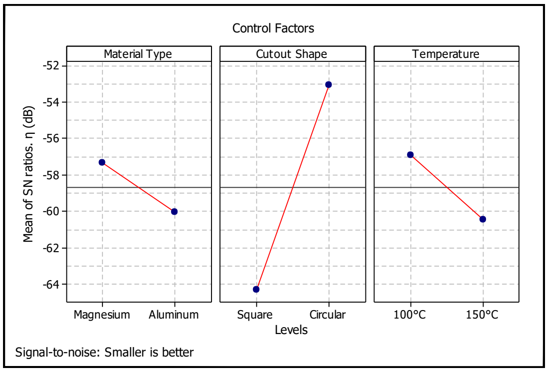


8. Analysis for deformation

Fig. 2. Numerical results for stress and deformation

4.1. Effect on stress and deformation

To see the effect of control factors on the von Mises stress and total deformation of plates, numerical analyses were conducted by L8 orthogonal design. The average data of von Mises stress and total deformation results for each parameter at all levels for numerical data and S/N data are plotted in Figure 3.



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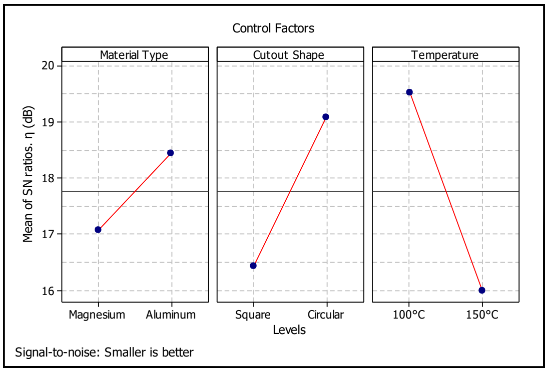

b)

Fig. 3. Main effects plot for S/N ratios: a) von Mises stress and b) total deformation

Figure 3 shows main effects for S/N ratios based on von Mises stress and total deformation. Increase of temperature from 100 °C to 150 °C causes an increase on stress and deformation of plates. This situation can be explained by elasticity modules and the coefficient of expansion of the materials. The stress and deformation values of plates with cutouts in the form of circular shapes is smaller compared to plates with cutouts in the form of square shapes. Magnesium alloy causes a decrease in stress and an increase in deformation of the plates compared to aluminum alloy. This can be explained by the fact that the modulus of elasticity of aluminum material is higher than that of magnesium material. This situation can be explained by the material properties. In addition, stress and deformation around the circular cutouts are homogeneously distributed relative to the square cutouts. This result confirms the obtained data.

4.2. Determination of optimum levels

To examine the importance of the control parameters such as material properties, cutout shape and temperature on von Mises stress and total deformation, analysis of variance (ANOVA) was carried out at 95% confidence level. ANOVA result was tabulated in Table 4.

Table 4. ANOVA result for von Mises stress and total deformation of plates

Source	DF	Von Mises Stress					Total Deformation				
		Seq SS	Adj MS	F	P	% Effect	Seq SS	Adj MS	F	P	% Effect
A	1	222071	222071	4.32	0.11	5.78	0.0008963	0.0008963	19.61	0.01	8.86
B	1	3038014	3038014	59.04	0	79.09	0.0032819	0.0032819	71.82	0	32.46
C	1	375056	375056	7.29	0.05	9.76	0.0057499	0.0057499	125.82	0	56.87
Error	4	205845	51461			5.36	0.0001828	0.0000457			1.81
Total	7	3840986				100	0.0101109				100
R-Sq = 94.64% and R-Sq(adj) = 90.62%							R-Sq = 98.19% and R-Sq(adj) = 96.84%				

According to Table 4, all parameters for deformation and the cutout shape and temperature for von Mises stress are significant parameters while material property is non-significant parameter for stress since P value is smaller than 0.05 value. The effective control factors on stress outcomes are cutout shape with 79.09% effect, temperature with 9.76% effect, and material property with 5.78 % effect, respectively. Significant control factors on deformation outputs are temperature with 56.87 % effect, cutout shape with 32.46 % effect, and material property with 8.86 % effect, respectively. To select the optimum levels of control factors, average data of stress and deformation characteristics for each level of each control factor were calculated in accordance with “smaller is better” quality characteristic. Response table obtained from these data were tabled in Table 5.

Table 5. Response table for von Mises stress and total deformation

Level	Von Mises Stress						Total Deformation					
	S/N ratio (dB)			Means (MPa)			S/N ratio (dB)			Means (mm)		
	A	B	C	A	B	C	A	B	C	A	B	C
1	-57.36	-64.32	-56.95	916.00	1698.80	866.10	17.07	16.44	19.52	0.1446	0.1543	0.1072
2	-60.05	-53.09	-60.47	1249.20	466.30	1299.10	18.45	19.08	16.00	0.1235	0.1138	0.1609
Delta	2.69	11.23	3.52	333.20	1232.50	433.00	1.38	2.65	3.52	0.0212	0.0405	0.0536
Rank	3	1	2	3	1	2	3	2	1	3	2	1

According to Table 5, the first levels of material type and temperature and the second level of cutout shape were determined as the optimal levels for von Mises stress. Also, the second levels of material type and cutout shape and the first level of temperature were found as the optimal levels for total deformation of the plates. Plates designed from circular cutouts and magnesium alloys are plates with the optimum levels for von Mises stress. In addition, plates designed using aluminum alloys and circular cutouts are plates with the optimal levels for total deformation.

4.3. Estimation of optimum stress and deformation characteristics

To optimum values of von Mises stress and total deformation were predicted using the optimal levels of important control factors. The important control factors were determined in accordance with ANOVA based on 95 % confidence level. The estimated mean of the response characteristics can be calculated [8] as:

$$\mu_E = \overline{A_\iota} + \overline{B_\iota} + \overline{C_\iota} - 2\overline{T_E} \tag{3}$$

where, $\overline{A_\iota}$, $\overline{B_\iota}$, and $\overline{C_\iota}$ define the control factors with optimum levels. $\overline{T_E}$ is overall mean of each response based on L8 orthogonal array. For von Mises stress, $\overline{A_1}$ = 916, $\overline{B_2}$ = 466.3, and $\overline{C_1}$ = 866.1 describe control factors with optimal levels. Also, $\overline{T_\sigma}$ = 1082.59 MPa was calculated. For total deformation, $\overline{A_2}$ = 0.1235, $\overline{B_2}$ = 0.1138, and $\overline{C_1}$ = 0.1072 expression control factors with optimal levels. In addition, $\overline{T_\delta}$ = 0.13405 was solved. Substituting the data of different terms in Equation 3, μ_σ = 83.22 MPa and μ_δ = 0.0764 mm were calculated. According to Table 6, differences between numerical and estimated data for von Mises stress and total deformation are found to be 26.34% and 8.67%, respectively

Table 6. Comparison of numerical and statistical results

Designation	Numerical Result	Predicted Result	% Different
$A_1B_2C_1$ for von Mises stress	315.96 MPa	83.22 MPa	26.34%
$A_2B_2C_1$ for total deformation	0.08366 mm	0.0764 mm	8.67%

5. Conclusion

This numerical and statistical study deals with the evaluate of the effect of material type, cutout shape and temperature on von Mises stress and total deformation analysis of plates under clamped boundary conditions. Numerical analyses were implemented by finite element software ANSYS Workbench and conducted by Taguchi L8 orthogonal array with three control factors. In statistical analysis, material type, cutout shape, and temperature were designated as control factors. Effects and optimum levels of control factors were detected using analysis of signal/noise ratio. Also, meaningful control factors were obtained using analysis of variance. Conclusions can be drawn as follows:

- Von Mises stress and total deformation of plates with cutouts in the form of circular shapes is smaller compared to plates with cutouts in the form of square shapes.
- Compared to magnesium alloy, aluminum alloy causes an increase in stress of plates and a decrease in total deformation of plates due to temperature increase.
- Increase of temperature from 100 °C to 150 °C causes an increase on stress and deformation of plates.
- The effective control factors on stress outcomes are found as cutout shape with 79.09% effect, temperature with 9.76% effect, and material property with 5.78% effect, respectively.
- Important control factors on deformation outputs are determined as temperature with 56.87% effect, cutout shape with 32.46% effect, and material property with 8.86% effect, respectively.
- The maximum von mises stress and total deformation distributions are monitored around the cutout shapes.
- Differences between numerical and estimated results for von Mises stress and total deformation are calculated as 26.34% and 8.67%, respectively

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