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Influence of Process Parameters on Form Factor Analysis During Micro Hole of AA 8011

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Abstract

In this work, micro holes have been made by a vertical machining centre. The experiments were conducted using Taguchi L9 design approach. Feed rate, spindle speed and air pressure were input control variable to vertical machining centre whereas Form factor of hole, Roundness of hole, Compactness of hole, Aspect ratio of hole and Form factor of delamination diameter, Roundness of delamination diameter, Compactness of delamination diameter, Aspect ratio of delamination diameter were the quality characteristics of shape factor. The influences of hole diameter on delamination diameter were analysed. The influences of process parameters on shape factor of hole and delamination diameter were analysed. Taguchi's method and Grey Relational Analysis was employed in this work to find the optimum process parameter of hole diameter and delamination diameter. The strong linear relationship was found between hole diameter and delamination diameter.

KEYWORDS: *AA 8011, micro-hole, vertical machining centre, Form factor.*

INTRODUCTION

Because of the properties of AA8011, the application areas are automobile, aircraft and marine. These types of component materials require a micro feature to join the other materials. Therefore, micro hole fabrication on AA8011 is chosen in this work. Among the variety of machine facility, computer numerical controlled vertical machining centre (CNC VMC) is chosen in this work. Most of the small scale industries have the CNC VMC machine facility and less cost compared to other non-conventional machining process. These micro feature creations using CNC VMC are unaware of small scale industrialist. Phillip et al., (2006) used the Micro-machining and micro/meso-scale machine tools to create micro-machined features range from 1 mm to 10 mm on the workpiece. Kuar et al., (2006) fabricated the micro-feature on zirconium oxide (ZrO_2) using CNC pulsed Nd:YAG laser. Kim et al., (2006) used the 250, 300, 500, and 700 µm in diameter electrode for fabricating micro hole on pyrex glass wafer using electro chemical machine. Venkatesh et al., (2014) fabricated the micro holes in the diameter 0.38 mm over the aluminium based composite specimen of thickness 0.4 and 0.5 mm. The micro electro chemical machine is used to make micro hole on sample. Biswas et al., (2015) made 51µm micro hole on alumina–aluminium composite using pulsed Nd:YAG laser. Widodo Redzuan and Kurniawan (2015) performed micro hole made in the diameter of 0.8 mm on AISI 304 austenitic stainless steel using vertical milling machine. Madhavi and Hiremath (2016) used the micro electro chemical machine to fabricate micro feature on borosilicate glass with tool diameter 0.3 mm tungsten carbide materials. Rajkumar et al., (2017) made micro holes in the size of 0.3, 0.4 and 0.5 mm on CFRP using vertical machining center.

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Aravind et al., (2017) made micro holes in diameter 0.7 mm, 0.8 mm and 0.9 mm on Carbon Fiber Reinforced Polymer (CFRP) using computer numerical controlled vertical drilling machine. Xu et al., (2018) carried out 0.5 mm micro hole creation process on soda lime glass using ECM. From this literature, most the micro feature creation works were made through non-conventional machine. No works were found in form factor analysis of micro-hole and delamination diameter on AA 8011. Few of the industrialists are involved in micro feature creation using conventional machine.

TAGUCHI METHODOLOGY

It is a statistical quality control methodology to design the experiment by using Minitab software and Design expert. This statistical software is used to reduce the cost of experiment. From the minimum number of an experiment, the quality characteristics of the machined or processed sample can be identified. It is widely accepted most of the researcher and industrialist.

EXPERIMENT DETAILS

The experiments were conducted using Taguchi L9 design approach. The Image and specification of vertical machining center is shown in Table 1. The micro drill image and its specification is shown in Table 2. The selection of process parameters were based on the trail experiments and machine capability, as shown in Table 3. The design of experiment for 3 levels and 3 factors is shown in Table 4. Feed rate, spindle speed and air pressure were input control variable to vertical machining center whereas Form factor (FF) of hole, Roundness (RD) of hole, Compactness (CT) of hole, Aspect ratio (AR) of hole and Form factor (FF) of delamination diameter, Roundness (RD) of delamination diameter, Compactness (CT) of delamination diameter, Aspect ratio (AR) of delamination diameter were the quality characteristics of shape factor. The shape descriptors (factors) were calculated by employing Equation 1 to Equation 4. The machined images were captured by employing Scanning Electron Microscope (SEM) and it is shown in Table 5. ImageJ software was used to measure the shape factor of hole and delamination diameter with accurately. The machined hole profile and delamination diameter profile were shown in Figure 1 and Figure 2 respectively.

Table 1 Image and Specification of vertical machining center

	Type of machine	Vertical machine center
	Brand	HARDING
	Model	VMC-800 II
	Control	Fanuc series 18-M
	Maximum Speed	12000 rpm
	Accuracy	±0.010 mm
	Travel length	500 x 800 x 500 mm
	Table size	920 x 510 mm

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Table 2 Image and Specification of micro tool bit

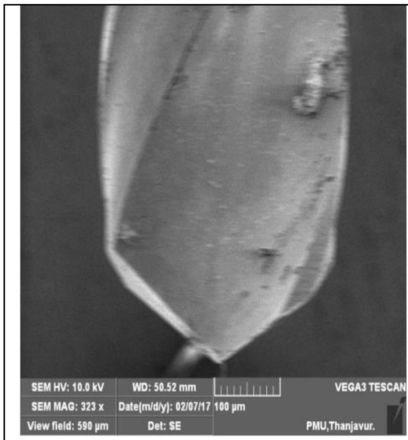	Drill diameter (mm)	0.4
	Drill name	Twist drill
	Manufacture	Tungaloy
	Drill materials	Carbide
	Shank type	Cylindrical
	Number of flutes	2
	Point angle (deg)	130
	Helix angle (deg)	30
	Total length (mm)	38

Table 3 Process parameters and its levels

Process parameters	Units	Notation	Levels		
			1	2	3
Feed rate	mm/min	f	1	3	5
Spindle speed	rpm	v	1500	2500	3500
Air pressure	bar	p	1	3	5

Table 4 Taguchi design for 3 level and 3 factors

Exp. No.	Feed rate (mm/min)	Spindle speed (rpm)	Air pressure (bar)
1	1	1500	1
2	1	2500	3
3	1	3500	5
4	3	1500	3
5	3	2500	5
6	3	3500	1
7	5	1500	5
8	5	2500	1
9	5	3500	3

Formula used for calculation:

$$\text{Form factor} = \frac{(4 \times \pi \ \ \text{Area})}{(\text{Perimeter})^2} \quad (1)$$

$$\text{Roundness} = \frac{4 \times \text{Area}}{\pi \times (\text{Major axis})^2} \quad (2)$$

$$\text{Compactness} = \frac{\sqrt{\left(\frac{4}{\pi}\right) \times \text{Area}}}{\text{Major axis}} \quad (3)$$

$$\text{Aspect ratio} = \frac{\text{Major axis}}{\text{Minor axis}} \quad (4)$$

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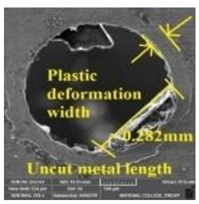
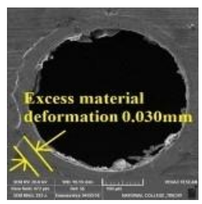
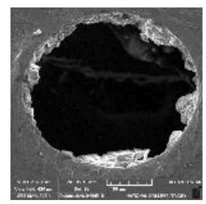
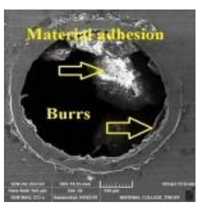
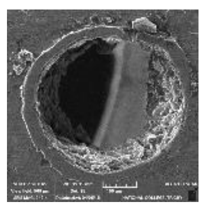
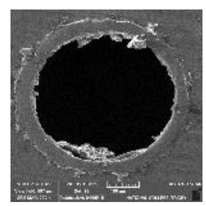
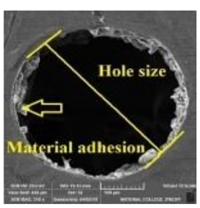
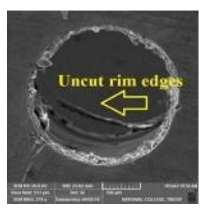
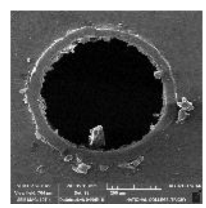
MEASUREMENT METHODOLOGY

The methodological procedures were used to measure the shape factor of hole and delamination diameter using ImageJ software.

Step 1: Import machined image photo (SEM image) into ImageJ software
Step 2: Convert RGB image into 8 bit image
Step 3: Calibrate the image
Step 4: By apply thresholding method to select the area
Step 5: Make binary images

Step 6: Wand tool to select the desired region (hole and delamination diameter)
Step 7: To measure the machined area, perimeter, major axis, minor axis of hole and delamination diameter.
Step 8: Equation 1 to Equation 4 used to calculate the FF, RD, CT and AR of hole and delamination diameter.

Table 5 Machined image of aluminium alloy

Exp. No.	SEM image of machined hole	Exp. No.	SEM image of machined hole	Exp. No.	SEM image of machined hole
1		4		7	
2		5		8	
3		6		9	

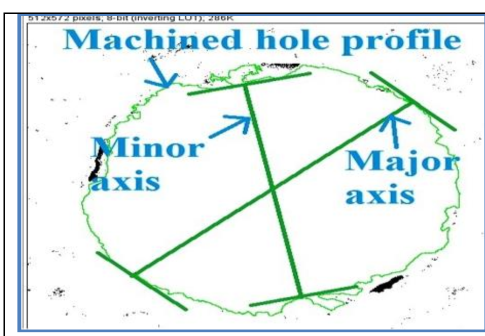


Figure 1 Machined hole profile

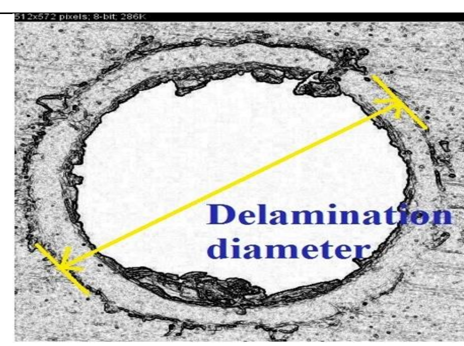


Figure 2 Machined delamination diameter profile

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RESULTS AND DISCUSSIONS

The micro-hole size of 0.4 mm can be successfully fabricating on AA 8011 using vertical machining center. Feed rate, spindle speed and air pressure were considered as input control parameters to vertical machining center. Feed rate and spindle speed were controlled by computer numerical control. Air pressure was controlled by employing separate compressor unit. Shape factor of FF, RD, CT and AR of hole and delamination diameter were measured by employing ImageJ software (https://imagej.nih.gov/ij/). The influences of hole diameter on delamination diameter were analysed. The influences of process parameters on shape factor of hole and delamination diameter were analysed. The optimum process parameters of shape factor of hole and delamination diameter were found by Taguchi's method. Grey Relational Analysis (GRA) was used to find the combined optimum process parameter of hole and delamination diameter. Analysis of Variance (ANOVA) was used to find the most influencing process parameter affecting the shape factor.

Influences of hole diameter on delamination diameter

The experimental result made by ImageJ and calculated the shape factor of micro-hole is shown in Table 6. The experimental result made by ImageJ and calculated the shape factor of delamination diameter is shown in Table 7. The aim to get the actual hole area, perimeter, major axis and minor axis were 0.13 mm^2, 1.26 mm, 0.4 mm and 0.4 mm respectively. But, the minimum obtained area, perimeter, major axis and minor axis were 0.115 mm^2, 1.202 mm, 0.385 mm and 0.38 mm respectively. These values were obtained at experimental number 7. The drill tool size was 0.4 mm. After drilling, the machined hole quality namely obtained hole area and hole perimeter were increases. This is due to the effect of process parameters on hole. The area, perimeter, major axis of hole and minor axis of hole were decreases. This is called as hole shrinkage (Merzouki et al. (2017)).

This is due to various reasons such as heat generation between the workpiece and tool, generation of radial force during drilling, relaxation of internal residual stresses, thermal expansion and diverse thermo mechanical loads applied between the workpiece and the tool. The induced radial force was affecting the hole quality (Pirtini et al. (2005)). The minimum obtained delamination that area, perimeter, major axis and minor axis were 0.156 mm^2, 1.404 mm, 0.446 mm and 0.445 mm respectively. These minimum values were obtained at experimental number 7 for area, major axis and minor axis and experimental number 3 for perimeter. This is due to the effect of process parameters and radial force generation on hole. The hole diameter was directly affecting the delamination diameter. Therefore, slope and intercept analysis of hole and delamination were performed using linear regression model. The influence of hole on delamination is shown in Figure 4. The linear regression model of area, perimeter, major axis and minor axis were developed between hole and delamination. The slope and intercept were analysed for area, perimeter, major axis and minor axis. The slope indicates the steepness of a line and the intercept indicates the location where it intersects an axis. The slope and the intercept define the linear relationship between two variables, and can be used to estimate an average rate of change. The greater magnitude of the slope and the steeper the line gave the greater the rate of change. For example: Linear regression model for area, $y = 1.553x - 0.0178$, where, y represents the area, 1.553x represents the slope value with x time, 0.0178 represents the intercept. Among the four equations, linear regression model gave the highest rate of change of area and following

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Table 6 Shape factor of micro-hole

Exp. No.	Measurement using ImageJ				Shape factor of micro-hole			
	Area	Perimeter	Major axis	Minor axis	Form factor	Roundness	Compactness	Aspect ratio
1	0.13	1.278	0.409	0.404	1.000	0.990	0.995	1.012
2	0.159	1.414	0.456	0.444	0.999	0.974	0.987	1.027
3	0.117	1.221	0.393	0.384	0.986	0.965	0.982	1.023
4	0.12	1.228	0.393	0.389	0.999	0.990	0.995	1.010
5	0.155	1.396	0.451	0.438	0.999	0.971	0.985	1.030
6	0.123	1.246	0.41	0.383	0.995	0.932	0.965	1.070
7	0.115	1.202	0.385	0.38	1.000	0.988	0.994	1.013
8	0.151	1.384	0.448	0.434	0.990	0.958	0.979	1.032
9	0.16	1.42	0.455	0.449	0.997	0.985	0.992	1.013

Table 7 Shape factor of micro-delamination diameter

Exp. No.	Measurement using ImageJ				Shape factor of Delamination diameter			
	Area	Perimeter	Major axis	Minor axis	Form factor	Roundness	Compactness	Aspect ratio
1	0.197	1.576	0.509	0.494	0.996	0.969	0.984	1.030
2	0.221	1.666	0.533	0.528	1.000	0.991	0.995	1.009
3	0.156	1.404	0.448	0.445	0.994	0.990	0.995	1.007
4	0.171	1.47	0.467	0.465	0.994	0.999	0.999	1.004
5	0.216	1.648	0.53	0.519	0.999	0.980	0.990	1.021
6	0.175	1.486	0.475	0.471	0.995	0.988	0.994	1.008
7	0.156	1.424	0.446	0.446	0.966	0.999	1.000	1.000
8	0.222	1.673	0.535	0.53	0.996	0.988	0.994	1.009
9	0.236	1.724	0.55	0.547	0.997	0.994	0.997	1.005

major axis, minor axis and perimeter. The negative value was shown in all the four equations. It represented that the values were decreases the quality characteristics of area, perimeter, major axis and minor axis. The intercept value of perimeter was highly dominated performance than others. Therefore, slope and intercept analysis found that area of hole and delamination diameter was highest rate of change for slope and minimum intercept value was found in the area of hole and delamination diameter. The R-squared values of all the four equation were above 0.9. It represented that the experimental data and prediction data were closely following the diagonal straight-line.

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Influences of feed rate on shape factor of hole and delamination diameter

The influences of feed rate on shape factor for hole and delamination diameter is shown in Figure 5. Shape factors are dimensionless quantities used in image analysis and microscopy that numerically describe the shape of a particle, independent of its size. Shape factors are calculated from measured dimensions, such as diameter, chord lengths, area, perimeter, centroid, moments, etc. The dimensions of the particles are usually measured from two-dimensional cross-sections or projections, as in a microscope field. Shape factors are often normalized, that is, the value ranges from zero to one. A shape factor equal to one usually represents an ideal case or maximum symmetry, such as a circle, sphere, square or cube. The feed rate was increased from 1 mm/min to 3 mm/min with the Form factor (FF) hole diameter increases from 0.995 to 0.998. This is due to the feed rate increased the cutting force and the axial loads on the cutting tool causing the enlargement of hole diameter (Niinomi (1998)). Also, the drilling vibration, chatter and drilling temperature appear to be playing a important role in the accuracy of drilled holes (Kurt et al. (2007)). It represented that hole diameter was closer to nominal size of hole (0.4 mm) at 2 mm/min feed rate. The feed rate was increased from 3 mm/min to 5 mm/min with the Form factor (FF) hole diameter decreases from 0.998 to 0.996. This 0.002 mm decreases FF was due to hole shrinkage and decreases of temperature.

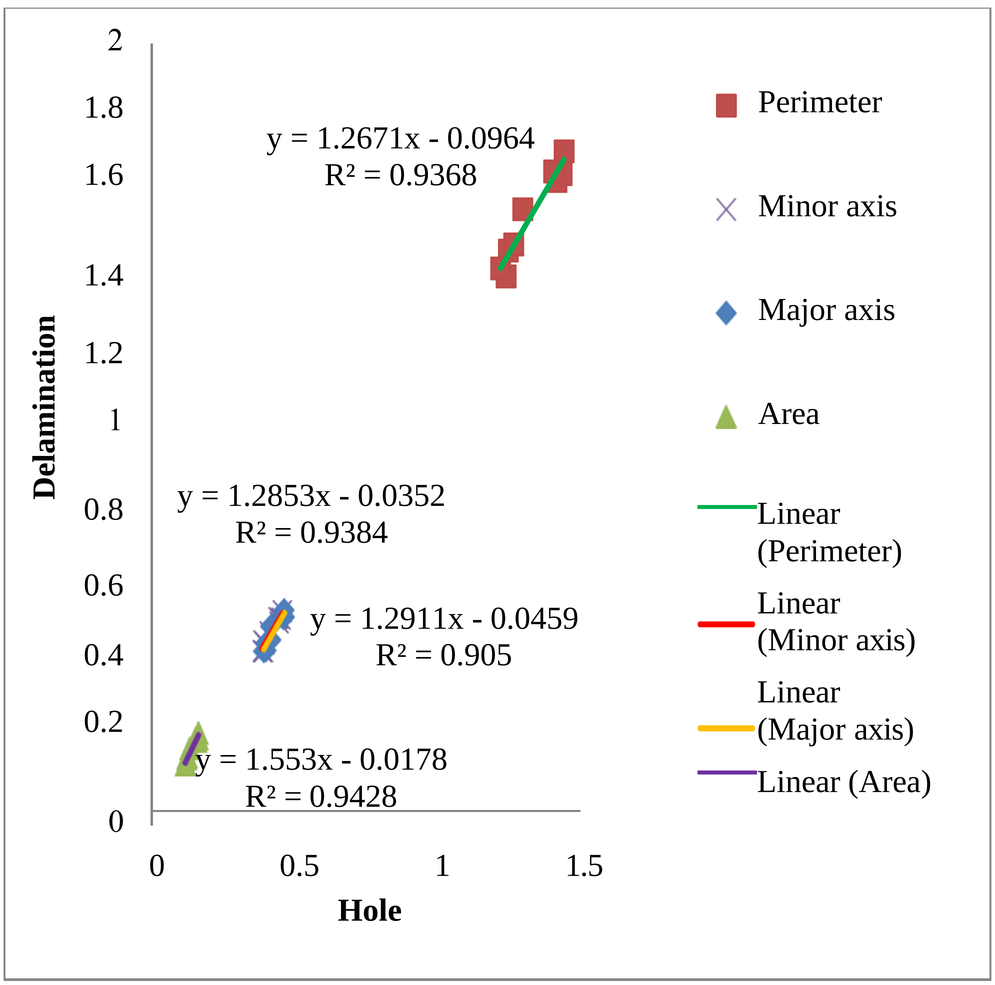

Figure 4 hole against delamination

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The feed rate was increased from 1 mm/min to 5 mm/min with the Form factor (FF) delamination diameter increases from 0.997 to 0.986. The decreases FF was due to hole shrinkage and decreases of temperature. The minimum delamination diameter or maximum FF was found at 1 mm/min feed rate. Similarly, the maximum Roundness (RD) of hole diameter and delamination diameter was found at 5 mm/min feed rate. The maximum Compactness (CP) of hole diameter was found at 1 mm/min and 5 mm/min and delamination diameter was found at 5 mm/min feed rate. One Aspect ratio (AR) value was represented perfect circle. The nearer to one value of Aspect ratio (AR) of hole diameter and delamination diameter was found at 5 mm/min. From the shape factor analysis, RD, CP and AR were found perfect circle at 5 mm/min feed rate except FF. Generally, the low feed rate gives high quality characteristics. The problems at low feed rate are long time to drilling resulting higher temperature generating between tool and workpiece due to friction, machining time increases cost and high tool wear.

Influences of spindle speed on shape factor of hole and delamination diameter

The influences of spindle speed on shape factor for hole and delamination diameter is shown in Figure 6. The spindle speed was increased from 1500 rpm to 3500 rpm with the Form factor (FF) hole diameter decreases from 1.000 to 0.993. This is due to higher frictional heat generating between tool and workpiece resulting FF of hole diameter decreases. Also, the drilling vibration, chatter and drilling temperature appear to be playing a important role in the accuracy of drilled holes (Kurt et al. (2007)). It represented that hole diameter was closer to nominal size of hole (0.4 mm) at 1500 rpm spindle speed. The spindle speed was increased from 1500 rpm to 2500 rpm with the Form factor (FF) delamination diameter increases from 0.985 to 0.998. The spindle speed was increased from 2500 rpm to 3500 rpm with the Form factor (FF) delamination diameter decreases from 0.998 to 0.995. The decreases FF was due to hole shrinkage and decreases of temperature.

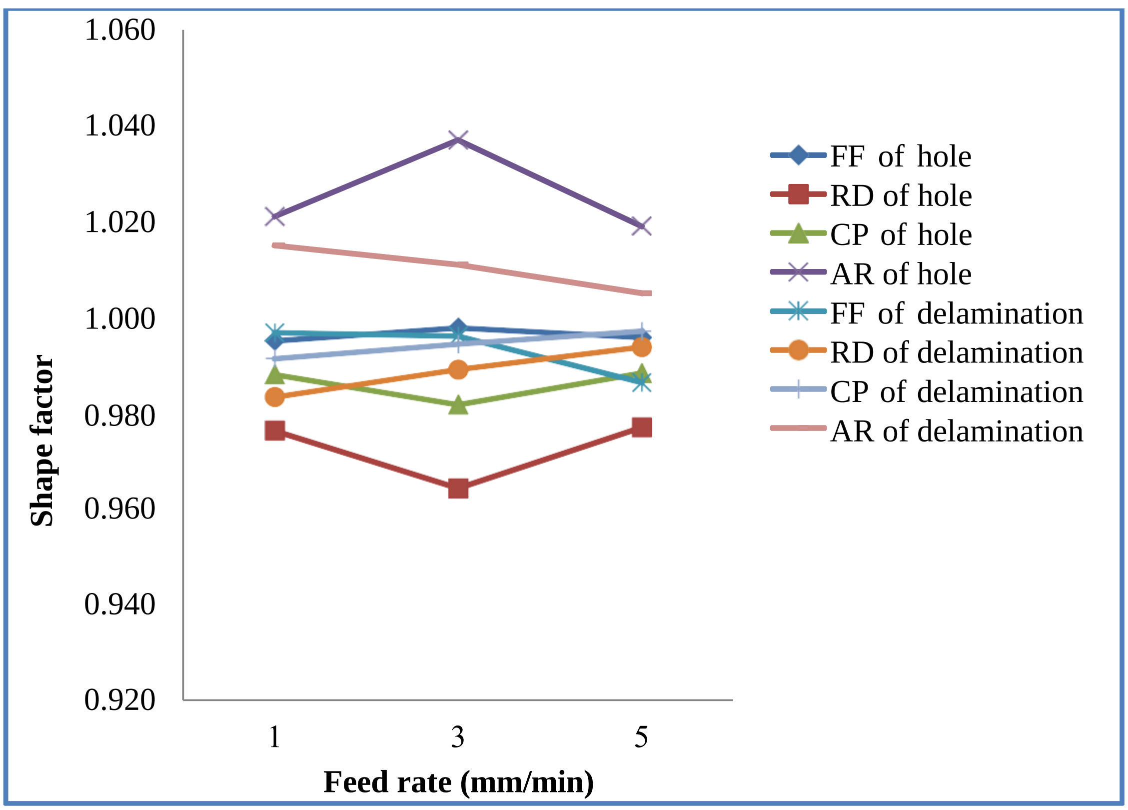

Figure 5 Feed rate against shape factor

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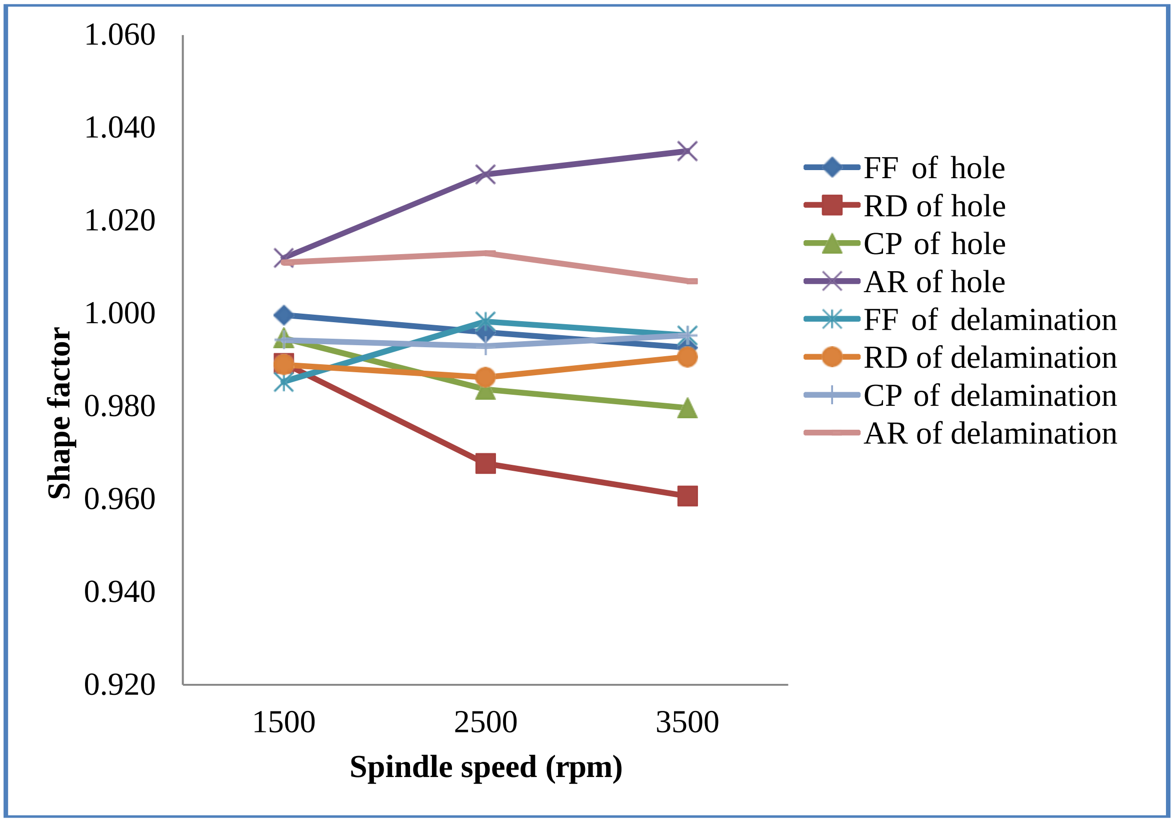

Figure 6 Spindle speed against shape factor

Influences of air pressure on shape factor of hole and delamination diameter

The influences of air pressure on shape factor for hole and delamination diameter is shown in Figure 7. The maximum FF, RD, CP and AR of hole and delamination factor were found at 3 kpa air pressure. The low air pressure has insufficient force to enter into micro-hole resulting higher lower shape factor (higher shape factor deviation). The optimum process parameter of hole diameter and delamination diameter were found and is shown in Table 8.

GREY RELATIONAL ANALYSIS

Taguchi's analysis has different optimum process parameters for form factor. In order to convert multiple objective process parameters in to the single objective process parameter. The grey relational analysis is employed in this work (Thirumalvalavan and Senthilkumar (2019)). The distinguishing coefficient has been taken as 0.125 for FF, RD, CP, and AR of hole diameter and delamination diameter. The rank of each trial has been tabulated based on the grey relational grade and evaluated grey relational grade for the responses for micro-drilling of AA 8011 as shown in Table 9. From Table 9, it is proved that experiments number 4 has the optimal set of parameters for best multi response characteristics such as FF, RD, CP, and AR of hole diameter and delamination diameter. The average grey relational grade value for every level of the input parameters have been computed by taking mean for every group levels of machining parameters and the values are given in Table 10.

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Since it represents the level of relationship between obtained sequence and reference sequence, the higher value of averaged grey relational grade denotes the very stronger relational ship between them. It clearly shows the optimal level of process parameters. The higher delta value indicates the most important nature of determining response in the machining process. The optimal process parameter setting condition is 3 mm/min feed rate, 1500 rpm spindle speed and 3 kpa air pressure. The results of ANOVA on all responses are given in Table 11. It is observed from Table 11 that highest contribution parameter was spindle speed, thus indicating that the spindle speed is significantly involving towards micro-drilling performance.

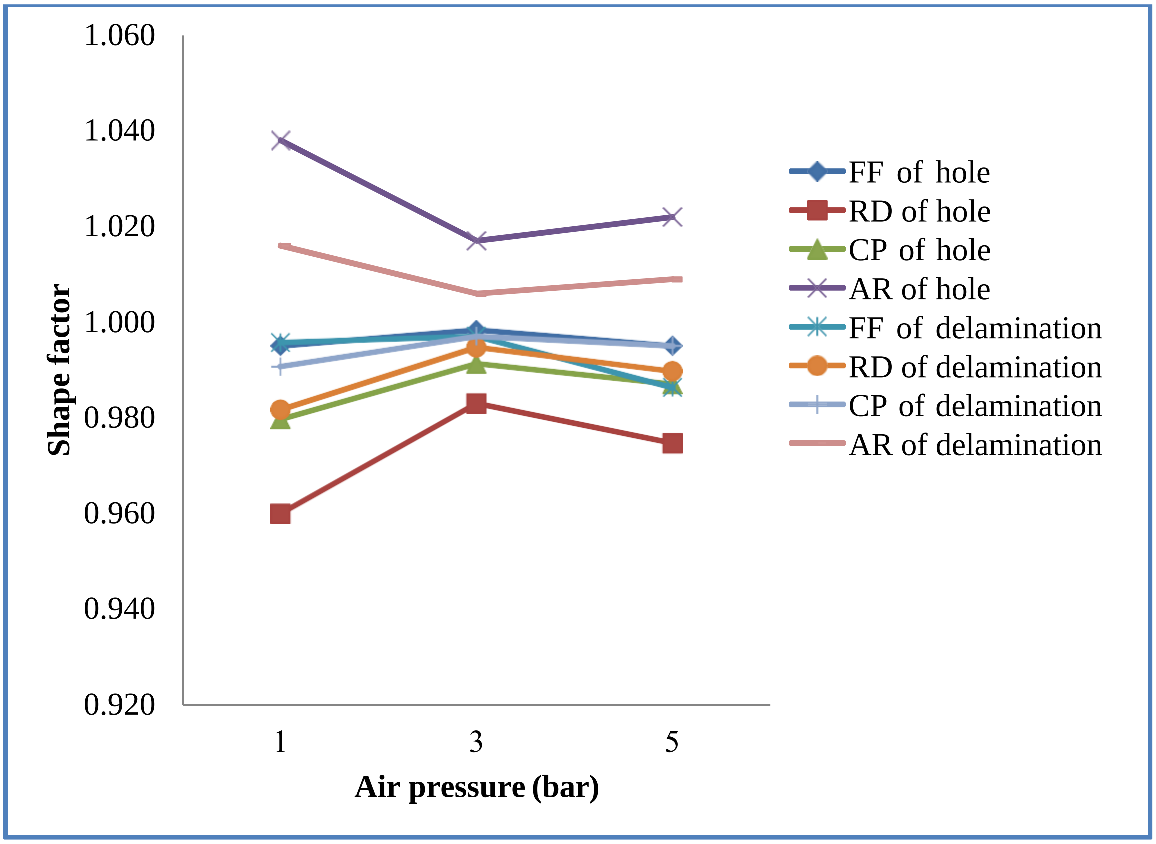

Figure 7 Air pressure against shape factor

Table 8 Summary of optimum process parameter

Shape factor	Hole diameter	Delamination diameter
FF	f2v1p2	f1v2p2
RD	f3v1p2	f3v3p2
CP	f3v1p2	f3v3p2
AR	f2v3p2	f1v2p1

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Table 9 Grey relational analysis calculation steps for hole and delamination diameter

Exp. No.	**Step 1**: Normalized value							
	Hole				Delamination			
	FF	RD	CP	AR	FF	RD	CP	AR
1	1.000	1.000	1.000	0.033	0.882	0.000	0.000	1.000
2	0.929	0.724	0.733	0.283	1.000	0.733	0.688	0.300
3	0.000	0.569	0.567	0.217	0.824	0.700	0.688	0.233
4	0.929	1.000	1.000	0.000	0.824	1.000	0.938	0.133
5	0.929	0.672	0.667	0.333	0.971	0.367	0.375	0.700
6	0.643	0.000	0.000	1.000	0.853	0.633	0.625	0.267
7	1.000	0.966	0.967	0.050	0.000	1.000	1.000	0.000
8	0.286	0.448	0.467	0.367	0.882	0.633	0.625	0.300
9	0.786	0.914	0.900	0.050	0.912	0.833	0.813	0.167
Exp. No.	**Step 2**: Grey relational co-efficient calculation							
	Hole				Delamination			
	FF	RD	CP	AR	FF	RD	CP	AR
1	1.000	1.000	1.000	0.115	0.515	0.111	0.111	1.000
2	0.636	0.312	0.319	0.149	1.000	0.319	0.286	0.152
3	0.111	0.225	0.224	0.138	0.415	0.294	0.286	0.140
4	0.636	1.000	1.000	0.111	0.415	1.000	0.667	0.126
5	0.636	0.276	0.273	0.158	0.810	0.165	0.167	0.294
6	0.259	0.111	0.111	1.000	0.459	0.254	0.250	0.146
7	1.000	0.784	0.789	0.116	0.111	1.000	1.000	0.111
8	0.149	0.185	0.190	0.165	0.515	0.254	0.250	0.152
9	0.368	0.592	0.556	0.116	0.586	0.429	0.400	0.130
No.	**Step 3**: Grey relational grade and rank calculation							
	GRG	Rank	No.	GRG	Rank	No.	GRG	Rank
1	0.606	3	5	0.347	6	9	0.397	5
2	0.397	4	6	0.324	7			
3	0.229	9	7	0.614	2			
4	0.619	1	8	0.232	8			

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Table 10 Mean GRG value

Level	Feed rate	Spindle speed	Air pressure
1	0.411	0.613	0.387
2	0.430	0.325	0.471
3	0.414	0.317	0.397
Delta	0.019	0.296	0.084
Rank	3	1	2

Table 11 ANOVA for GRG value

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value	Contribution percentage
Feed rate	2	0.0006	0.0006	0.0003	0.04	0.96	0.32
Spindle speed	2	0.1706	0.1706	0.0853	11.12	0.08	85.65
Air pressure	2	0.0126	0.0126	0.0063	0.82	0.55	6.33
Error	2	0.0154	0.0154	0.0077			7.70
Total	8	0.1992					100
S = 0.0876071 R-Sq = 92.30% R-Sq(adj) = 69.18%							

CONFIRMATION TEST

In this study, a confirmation experiment were performed by utilizing the optimal machining parameters (f2v1p2) for FF, RD, CP, and AR of hole diameter and delamination diameter are shown in Table 12 and illustrate the results of initial and optimal micro-drilling performance. The optimized parameter shows significant improvement in performance.

Table 12 Confirmation test

		Initial raw data	Prediction	Experimental
Conditions	Shape factor	f1v1p1	f2v1p2	f2v1p2
Hole	FF	1.000		0.999
	RD	0.990		0.990
	CP	0.995		0.995
	AR	1.012		1.010
Delamination	FF	0.996		0.994
	RD	0.969		0.999
	CP	0.984		0.999
	AR	1.030		1.004
GRG		0.606	0.677	0.619
Improvement in GRG =0.013				

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DEFECTS ANALYSIS

The SEM image of machined micro-hole is shown in Table 5. The plastic deformation was observed in all the experimental conditions. This is due to the effect of process parameter, frictional heat and induced force on hole rim. The material adhesion was observed at experimental number 2 and 3. This is formed between the sliding surfaces and deformation presents due to the interlocking of micro asperities under the applied load. In order to eliminate the adhesion formation the additional force is required in the tool. Also, uncut metal length and uncut rim edges was formed at entry and exit of hole. This is also due to material adhesion. The excess material deformation was found at entry side of hole. This is due to sudden force generation and vibration of tool or machine.

CONCLUSIONS

0.4 mm drill diameter made micro-hole on AA 8011 using computer numerical controlled vertical machining centre. By applying image processing tool, form factor (descriptor) of micro-hole diameter and micro-delamination diameter of FF, RD, CP and AR have been performed and the following conclusions have been made.

1. The strong linear relationship was found between the hole diameter and delamination diameter.
2. The maximum form factor was obtained at 5 mm/min feed rate, 1500 rpm spindle speed and 3 kpa air pressure.
3. Spindle speed was most dominated factor to affecting performance of form factor.
4. Form factor performance was improved by using grey relational analysis.
5. Plastic deformation, material adhesion, uncut rim edges, uncut metal length and excess material deformation were observed in all the experiments.
6. In future, 0.1 mm drill diameter can be performed on different aluminium alloy series.

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