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INFLUENCE OF THE PROCESS PARAMETERS AND THE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS ON THE BURR HEIGHT AND THE SURFACE ROUGHNESS IN DRY DRILLING

VPLIV PARAMETROV PROCESA IN MEHANSKIH LASTNOSTI ALUMINIJEVIH ZLITIN NA VIŠINO IGLE IN HRAPAVOST POVRŠINE PRI SUHEM VRTANJU

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In this paper, the effect of the mechanical properties of aluminum alloys, cutting speed, feed rate and the drill diameter on burr height and surface roughness of drilling holes were investigated, using the Taguchi method. Al-2024, Al-7075 and Al-7050 were selected as the workpiece materials for experiments. The analysis of variance and signal-to-noise ratio were employed to analyze the effect of the drilling parameters. The results of the statistical analysis indicated that feed rate and cutting speed minimize significantly both the height of the exit burrs and the surface roughness. Moreover, the mechanical properties of the workpieces are different influential factors on both responses.

Keywords: drilling, burr height, surface roughness, Al-2024, Al-7075, Al-7050

Raziskan je vpliv mehanskih lastnosti aluminijevih zlitin, hitrosti rezanja in podajanja ter premera svedra na višino igle in hrapavost površine vrtane površine z uporabo Taguchi metode. Za preizkuse so bile izbrane zlitine Al-2024, Al-7075 in Al-7050. Analize variance in intenzitete signal-ozadje so bile uporabljene za določitev vpliva parametrov vrtanja. Rezultati statistične analize so pokazali, da hitrosti podajanja in rezanja zmanjšujeta višino izhodne igle in hrapavost površine. Tudi mehanske lastnosti obdelovanca imajo različen vpliv na oba odgovora.

Ključne besede: vrtanje, višina igle, hrapavost površine, Al-2024, Al-7075, Al-7050

1 INTRODUCTION

Drilling is one of the most important material removal process that has been widely used in the aerospace, aircraft and automotive industries. Although modern metal-cutting methods, including electron-beam machining, ultrasonic machining, electrolytic machining and abrasive jet machining, have improved in the manufacturing industry, conventional drilling still remains one of the most common machining processes[1,2]. Aluminum is used in many industrial areas to make different products and it is significant for the world economy. Structural components made from aluminum and aluminum alloys are vital in the aerospace industry and very important in other areas of transportation and building in which durability, strength and light weight are expected[3].

The drilling process produces burrs on both the entrance and the exit surfaces of the workpiece. The exit burr is part of the material extending off the exit surface of the workpiece. Most burr-related problems in drilling are caused by the exit burr because it is much larger than the entrance burr[4]. The presence of these exit burrs requires additional manufacturing steps for disassembly and deburring. These additional steps are typically not easy to automate and are generally performed manually[5]. Burr formation affects workpiece accuracy and quality in several ways: deterioration of the surface quality, dimensional distortion on the part edge, challenges to assembly and handling caused by burrs in sensitive locations on the work and damage done to the workpiece subsurface from the deformation associated with burr formation[6].

In several studies burr formation and surface roughness were investigated. Nouari et al.[7] examined the effect of the machining parameters on the hole-surface roughness and diameter deviations for different coated drills. The results show that, small constant feed rate, low cutting speeds are appropriate for the dry machining of AA-2024. Kilickap[6] presented an application of Taguchi and response surface methodologies for minimizing the burr height and the surface roughness in drilling Al-7075. The optimization results showed that the combination of low cutting speed, low feed rate and high point angle is necessary to minimize both burr height and surface roughness. Kurt et al.[3] investigated the role of different coatings, point angle and cutting parameters on the hole quality in the drilling of Al-2024 alloy and concluded that the cutting parameters and the coatings have different effects on hole quality. They have obtained effective results using a low cutting speed and feed rate. Ko and Lee[8] used several materials that were drilled by several cutting conditions, velocity and feed rate. They indicated that burr formations were highly dependent on the material properties, the drill geometry and the cutting condition. Lauderbaugh[9] used simulation tools and analysis of variance to identify the influence of process parameter on the height of exit burrs and concluded that feed rate, chisel-edge-to-drill diameter ratio, drill diameter, yield strength and point angle are significant for the height of exit burrs. Ko et al.[10] carried out an experimental investigation of the role of various shapes of drills and materials (SM45C, SS400, A6061-T6 and A2024-T4) on the burr in drilling. Their experimental results showed that the burr height from ductile materials is larger than from brittle materials. Kurt et al.[11] investigated the influence of the cutting parameters and the mechanical properties of a workpiece on the burr formations in a dry drilling process. His experimental results showed that the machining parameters and the mechanical properties of a workpiece effect the burr formation. In addition to these they have classified the burrs into three types. Kalidas et al.[12] compared the performance of the three types of coatings on the hole quality under dry- and wet-drilling conditions of aluminum alloys. The result of the experiments indicates that, the use of coatings did not seem to affect the surface roughness of the hole produced.

In this study a statistical analysis of the experimental data of the cutting parameters and the mechanical properties of aluminum alloys on the burr height and surface roughness of the produced hole in the dry drilling of Al-2024, Al-7075 and Al-7050 have been investigated and analyzed with the Taguchi method.

2 MATERIALS, CUTTING CONDITIONS AND PLAN OF EXPERIMENTS

Burr height and the surface roughness of the drilled hole surface were determined by cutting condition. The drilling experiments were conducted in dry cutting conditions on a Johnford VMC model three axes CNC milling machine with a Fanuc controller. In this study, Al-2024, Al-7075 and Al-7050 were chosen as the work materials with the specimen dimensions 200 mm × 140 mm × 30 mm. The mechanical properties of the three aluminum alloys are presented in **Table 1**.

Uncoated, conventional, high-speed-steel twist drills with diameters of 8 mm, 10 mm and 12 mm were used for drilling experiment. A new drill bit was used for each drilling experiment. The burr heights (H) and surface roughness (R_a, the arithmetic average) of each drilled hole were measured by means of an optical microscope and a Mahr Perthometer surface roughness tester using a meter cut off of 5.6 mm. The burr height and the surface roughness of the machined hole measurement points of the workpiece are shown in **Figure 1**. Each specimen

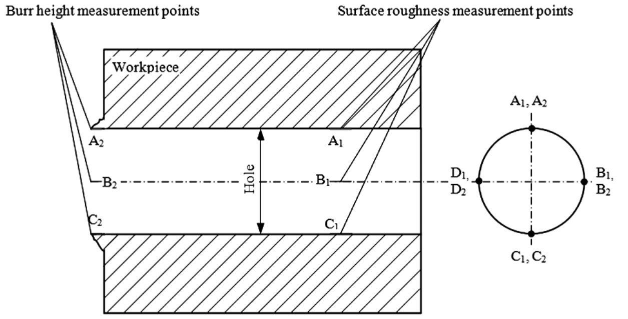

Figure 1: Burr height and surface-roughness measurement points of the produced hole
Slika 1: Točke meritev višine igle in hrapavosti površine pri izvrtinah

was measured from four different points (0°, 90°, 180° and 270°) for both, burr height and surface roughness.

The drilling experiments were planned using Taguchi's orthogonal array. Three experimental parameters were the cutting speed, feed rate and drill diameter were selected for the present investigation. Three levels of each control factor were taken into account. Taguchi's orthogonal array of L_{27} was chosen for the experimental plan. The considered experimental factors and their levels are listed in **Table 2**.

Table 1: Mechanical properties of Al-2024, Al-7075 and Al-7050 materials
Tabela 1: Mehanske lastnosti zlitin Al-2024, Al-7075 in Al-7050

Materials	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation %	Hardness (HRB)
Al-2024	469	324	17	75
Al-7075	570	505	11	87
Al-7050	521	467	10	84

Table 2: Control factors and their levels used for drilling experiments
Tabela 2: Kontrolni dejavniki in njihov nivo, uporabljen pri preizkusih vrtanja

Symbol	Factors	Unit	Level		
			1	2	3
A	Cutting speed	m/min	20	30	40
B	Feed rate	mm/r	0.05	0.1	0.15
C	Drill diameter	mm	8	10	12

3 EXPERIMENTAL RESULTS AND ANALYSIS

The Taguchi method is very popular for solving optimization problems in the field of manufacturing engineering[13]. In this method, the term "signal" (S) represents the desired value and the "noise" (N) represents the undesired value. The objective of using the *S/N* ratio is a measure of the performance to develop products and processes that are insensitive to noise factors. The *S/N* ratio indicates the degree of predictable performance of a product or process in presence of noise factors. The process parameter settings with the highest *S/N* ratio always yield the optimum quality with minimum variance. The difference between the functional

Table 3: Experimental layout using L_{27} orthogonal array and experimental values
Tabela 3: Načrt preizkusov z uporabo ortogonalne razporeditve L_{27} in vrednosti preizkusov

Trial no.	Factor Level			Al-2024		Al-7075		Al-7050	
	A	B	C	*H*/mm	R_a/µm	*H*/mm	R_a/µm	*H*/mm	R_a/µm
1	1	1	1	3.29	6.200	1.43	2.967	1.14	2.042
2	1	1	2	3.32	6.188	1.55	3.061	1.45	2.275
3	1	1	3	3.54	6.484	1.68	3.073	1.60	2.352
4	1	2	1	4.27	6.395	1.64	3.112	1.22	2.331
5	1	2	2	4.40	6.580	1.88	3.335	1.55	2.422
6	1	2	3	4.51	6.934	1.92	3.429	1.65	2.421
7	1	3	1	5.28	6.883	2.76	3.265	2.21	2.487
8	1	3	2	4.84	6.930	2.59	3.312	2.25	2.529
9	1	3	3	5.06	7.234	2.62	3.451	2.45	2.587
10	2	1	1	3.04	6.847	1.73	3.088	1.28	2.242
11	2	1	2	3.22	7.090	2.12	3.208	1.89	2.421
12	2	1	3	3.30	7.158	2.30	3.322	1.31	2.582
13	2	2	1	4.04	6.906	1.87	3.457	1.98	2.627
14	2	2	2	3.81	7.120	1.98	3.742	2.42	2.728
15	2	2	3	5.27	7.476	2.88	3.751	2.38	2.838
16	2	3	1	6.28	7.118	2.44	3.634	2.11	2.854
17	2	3	2	6.44	7.515	2.65	3.361	2.20	2.975
18	2	3	3	6.61	7.700	2.93	3.814	2.56	3.081
19	3	1	1	3.51	7.322	1.93	3.676	1.72	2.679
20	3	1	2	5.75	7.441	1.93	3.332	1.45	2.751
21	3	1	3	5.01	7.397	2.13	3.751	1.97	2.883
22	3	2	1	6.21	7.809	2.92	3.209	2.21	2.667
23	3	2	2	5.57	7.930	2.78	3.831	2.55	2.948
24	3	2	3	6.31	7.974	2.42	3.928	2.22	3.027
25	3	3	1	6.58	7.970	2.97	3.287	2.63	3.031
26	3	3	2	6.42	8.114	3.75	4.107	2.67	2.942
27	3	3	3	4.89	7.939	3.78	4.321	3.53	3.288

Table 4: Response table for burr height and surface roughness
Tabela 4: ANOVA-rezultati za višino igle

Factors	Mean *S/N* ratios (dB) for *H*			Mean *S/N* ratios (dB) for R_a		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
Al–2024						
Cutting speed	–12.50[2]	–12.99	–14.80	–16.44[1]	–17.16	–17.80
Feed rate	–11.34[1]	–13.72	–15.23	–16.76[2]	–17.16	–17.47
Drill diameter	–13.14[3]	–13.47	–13.68	–16.94[3]	–17.13	–17.33
Al–7075						
Cutting speed	–5.813[2]	–7.181	–8.482	–10.15[1]	–10.83	–11.36
Feed rate	–5.326[1]	–6.874	–9.276	–10.28[2]	–10.94	–11.12
Drill diameter	–6.516[3]	–7.173	–7.788	–10.35[3]	–10.79	–11.20
Al–7050						
Cutting speed	–4.450[2]	–5.851	–7.073	–7.524[1]	–8.606	–9.269
Feed rate	–3.588[1]	–5.886	–7.900	–7.805[2]	–8.490	–9.103
Drill diameter	–4.924[3]	–6.002	–6.448	–8.076[3]	–8.478	–8.844

1, 2 and 3: Optimum level and Rank

value and the objective value is emphasized and identified as the loss function. The loss function is derived as Eq. (1)

$$L(y)=\frac{L''(m)(y-m)^2}{2!}=k(y-m)^2=k(MSD) \quad (1)$$

where *L(y)* is the loss function, *y* is the value of the quality characteristic, *m* is the target value of *y*, *k* is the commensurately constant, which depends on financial criticality of *y,* and *MSD* is the mean square deviation. Eq. (1) can be expressed by the signal-to-noise ratio (η) and can be rewritten as:

$$\eta=-10\lg_{10}(MSD) \quad (2)$$

The value of the loss function is further transformed into a signal-to-noise (*S/N*) ratio. In the present investigation, the objective is to minimize the burr height and the surface roughness; therefore, "smaller is better" as a quality characteristic is selected, which is a logarithmic function given as:

$$S/N(\eta)=-10\lg_{10}\left(\frac{1}{r}\sum_{i=1}^{r}R_i^2\right) \quad i=1,2,...,r \tag{3}$$

where R_i is the value of the burr height or the surface roughness for the *i*th trial in *r* number of measurements[14].

The experimental values obtained from the experiments related to burr height and surface roughness are illustrated in **Table 3**. The *S/N* ratios for the burr height (H) and the surface roughness (R_a) were calculated using the output parameter values given in **Table 3**. The *S/N* ratio for each parameter level was calculated by averaging the *S/N* ratios obtained when the parameter maintained at that level. **Table 4** shows the *S/N* ratio obtained for different parameter levels.

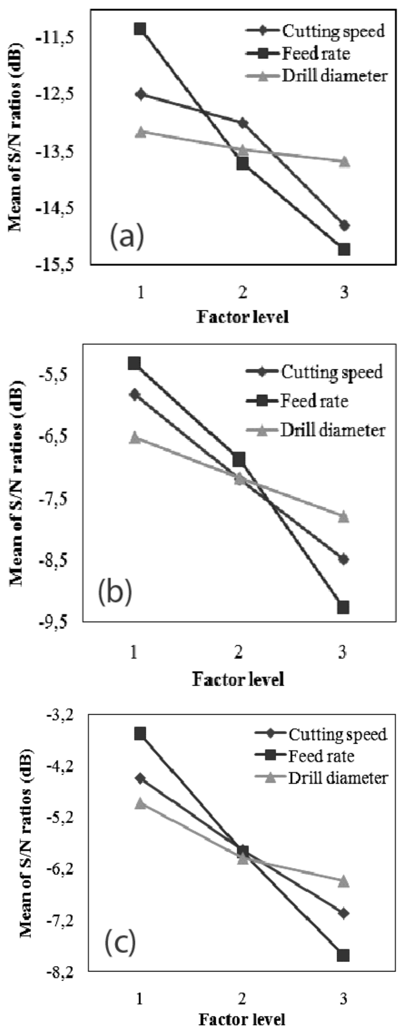

Figure 2: Effect of cutting parameters on the burr height: a) Al-2024, b) Al-7075 and c) Al-7050

Slika 2: Vpliv parametrov rezanja na višino igle: a) Al-2024, b) Al-7075 in c) Al-7050

Table 5: The result of ANOVA for burr height
Tabela 5: ANOVA-rezultati za višino igle

Factors	*Dof*	*SS*	*V*	*F*	*P*/%
Al-2024					
Cutting speed	2	8.0732	4.0366	7.60*	21.31
Feed rate	2	18.9565	9.4782	17.84*	50.04
Drill diameter	2	0.2276	0.1138	0.21	0.60
Error	20	10.6262	0.5313		28.05
Total	26	37.8834			100
Al-7075					
Cutting speed	2	2.3905	1.1953	13.76*	23.98
Feed rate	2	5.3525	2.6762	30.80*	53.68
Drill diameter	2	0.4903	0.2451	2.82	4.92
Error	20	1.7376	0.0869		17.42
Total	26	9.9709			100
Al-7050					
Cutting speed	2	1.6389	0.8194	10.37*	20.27
Feed rate	2	4.3023	2.1511	27.23*	53.19
Drill diameter	2	0.5671	0.2835	3.59*	7.01
Error	20	1.5800	0.0790		19.53
Total	26	8.0883			100

* Significant at 95 % confidence level

Table 6: The result of ANOVA for surface roughness
Tabela 6: ANOVA-rezultati za hrapavost površine

Factors	*Dof*	*SS*	*V*	*F*	*P*/%
Al-2024					
Cutting speed	2	5.6317	2.8159	131.94*	69.83
Feed rate	2	1.5560	0.7780	36.45*	19.30
Drill diameter	2	0.4501	0.2250	10.54*	5.58
Error	20	0.4268	0.0213		5.29
Total	26	8.0646			100
Al-7075					
Cutting speed	2	1.09547	0.54773	13.10*	35.90
Feed rate	2	0.56992	0.28496	6.81*	18.68
Drill diameter	2	0.54954	0.27477	6.57*	18.00
Error	20	0.83654	0.04183		27.42
Total	26	3.05146			100
Al-7050					
Cutting speed	2	1.28385	0.64192	87.02*	54.05
Feed rate	2	0.69896	0.34948	47.38*	29.43
Drill diameter	2	0.24479	0.12240	16.59*	10.31
Error	20	0.14753	0.00738		6.21
Total	26	2.37513			100

*Significant at 95 % confidence level

The response graphs for the *S/N* ratios of the burr height and the surface roughness are shown in **Figures 2** and **3**, respectively. It is observed from the *S/N* response graph that the optimum parameter level combinations for the minimum values of Al-2024, Al-7075 and Al-7050 are $A_1B_1C_1$, for both burr height and surface roughness. As shown in **Table 4** and **Figure 2**, the feed rate is the dominant parameter on the burr height followed by the cutting speed. The drill diameter has a lower effect on burr height. Although a lower burr height is always preferred, burr formation in drilling is not desirable. In the present investigation, when cutting speed 20 m/min, feed rate 0.05 mm/r and drill diameter 8 mm are used, the burr height is minimized. The height of the exit burr increases as the feed rate, the cutting speed and the drill diameter increase. As shown in **Table 4** and **Figure 3**, cutting speed is the dominant parameter on surface roughness, followed by the feed rate. The drill diameter has a lower effect on surface roughness. In the present investigation, when applied by cutting speed 20 m/min, feed rate 0.05 mm/r and the drill diameter 8 mm, the surface roughness is minimized. The roughness of the drilled surface increases as the feed rate, the cutting speed and the drill diameter increase.

The results of the analysis of variance (ANOVA) for the burr height are presented in **Table 5**. From the analysis, for all three aluminum alloys the feed rate is a highly significant factor and plays a major role in affecting the burr height. It can be observed from **Table 5** that cutting speed also affects the burr height. The

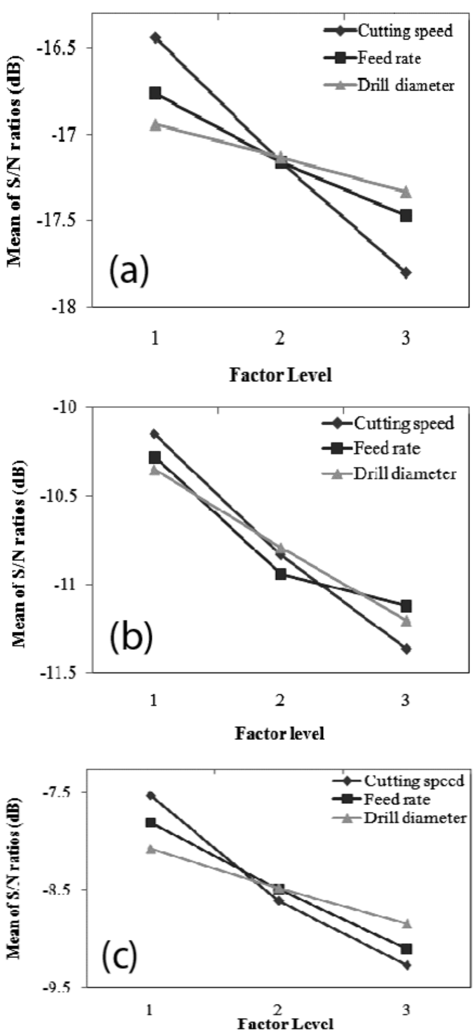

Figure 3: Effect of cutting parameters on the surface roughness: a) Al-2024, b) Al-7075 and c) Al-7050

Slika 3: Vpliv parametrov rezanja na hrapavost površine: a) Al-2024, b) Al-7075 in c) Al-7050

effect of the drill diameter does not make any impact on the responses, except for Al-7050. Percent (%) is described as the significance rate of the process parameters on the burr height. It can be observed from the ANOVA Table that the cutting speed, feed rate and drill diameter are effect on the burr height 21.31 %, 50.04 % and 0.60 %; 23.98 %, 53.68 % and 4.92 %; 20.27 %, 53.19 % and 7.01 % in drilling of Al-2024, Al-7075 and Al-7050, respectively.

The results of the ANOVA for the surface roughness are presented in **Table 6**. From the analysis, for the all three aluminum alloys the cutting speed is a highly significant factor and plays a major role in affecting the surface roughness. It can be observed from **Table 6** that the feed rate and the drill diameter also affect the surface roughness. It can be observed from the ANOVA Table that cutting speed, the feed rate and the drill diameter are effect on the surface roughness 69.83 %, 19.30 % and 5.58 %; 35.90 %, 18.68 % and 18.00 %; 54.05 %, 29.43 % and 10.31 % drilling of the Al-2024, Al-7075 and Al-7050, respectively.

A series of experiment were conducted on three types of aluminum. The properties of the workpiece material have a significant influence on the burr height[15]. The burr formation process is heavily dependent on the yield strength, ultimate strength[9] and ductility[4]. Also considering the ductility of materials represented as elongation[8] in **Table 1** for the alloys Al-2024, Al-7075 and Al-7050. The higher value of elongation represents better ductility of the material. Al-2024 shows more ductility than the Al-7075 and Al-7050 alloys. The elongation percentage of workpieces used in the experiments affects the formation of the burr height and the surface roughness. The amount of burr around the hole, which is drilled in Al-2024 alloy material is greater for Al-7075 and Al-7050, because Al-2024 is more ductile than Al-7075 and Al-7050. Also the difference of burr height in Al-7075 and Al-7050 is not large, Al-7050 produces the smaller burr. As a result, much more burr occurs in ductile materials. This tendency was also mentioned by various other researchers[4,8–10]. In summary, burrs are formed as a result of plastic deformation and fracture. The final burr geometry determined by the amount of plastic deformation is determined by the ductility of the material represented as elongation[8].

Al-7050 alloy machined surface, shows a lower value of the surface roughness compared to Al-2024 and Al-7075 alloys. Higher surface roughness values of Al-2024 alloy can be explained by the highly ductile nature of the alloy, which increases the tendency to form a built-up edge (BUE). A relatively higher workpiece ductility increases the BUE formation tendency[16]. The presence of the BUE in the drilling process causes an increase in the tool wear and a rougher surface finish.

4 CONCLUSIONS

In order to minimize the burr height and the surface roughness of Al-2024, Al-7075 and Al-7050, the effects of various cutting parameters have been investigated in drilling using the Taguchi method and the analysis of variance. Based on the *S/N* ratios and the ANOVA results it is concluded that feed rate was the most influential controllable factor among input parameters which affect the burr height. The cutting speed was the second factor at burr formation. The drill diameter has the lowest effect on burr height. In view of the surface roughness, cutting speed is a dominant parameter and it is followed by feed rate and drill diameter, respectively. Moreover, the best parametric combination of the three control factors minimizing both the burr height and the surface roughness were as follows: 20 m/min cutting speed, 0.05 mm/r feed rate and 8 mm drill diameter.

The mechanical properties of the workpieces are an influential factor on burr height and surface roughness formed at the hole. Due to the ductility of the material, the amount of burr around the hole in Al-2024 alloy material is much more than in Al-7075 and Al-7050, and it can be explained with elongation. In addition, the surface roughness obtained by Al-2024 is worse than by Al-7075 and Al-7050 alloys. The higher surface roughness values of the Al-2024 alloy can be explained by the highly ductile nature of the alloy.

It is highly important to avoid burr formation, to minimize it or to take it under control as an additional manufacturing step is needed in order to be able to eliminate the burrs formed by drilling. Minimization of burr formation is an important problem of manufacturing. The analysis of variance and Taguchi techniques were applied in order to determine the effects of the drilling parameters. Through the utilizing optimal conditions obtained with S/N ratio, the burr around the hole is minimized which contibutes the reduction of the overall manufacturing cost by reducing the number of processing requirement.

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