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Burr height and hole diameter error minimization in drilling of AL6063/15%/SiC composites using HSS step drills †

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Abstract

In drilling process, burr plays an important role on the quality parts. It is necessary to minimize the burr height. This paper presents the effect of CNC drilling process parameters like cutting speed, feed rate, step angle and cutting environment on burr height and hole diameter error of Al6063/15%/SiC composites. The composites are fabricated using mechanical stir casting. An experimental study on composites was conducted using three HSS drills. The Taguchi design of experiments and analysis of variance (ANOVA) are used to optimize the response for Al6063/15%/SiC composites. The results revealed that the quality of the holes can be improved by proper selection of cutting process parameters. SEM analysis and XRD analysis are also carried for composite, drilled surface and drill bits. These analysis provide the good agreement with the effect of cutting parameters on burr height and hole diameter error.

Keywords: CNC drilling machine; Taguchi; Al6063/15%/SiC composite; Burr height; Hole diameter error; XRD; SEM

1. Introduction

Composite materials have high tensile strength, high toughness, high hardness and high strength to weight ratio etc. Due to these properties, composite materials are replaced from conventional materials in several fields. They are used in the aerospace, medical and automobile industry, but also in consumer products such as bicycle parts, sports equipment etc. The drilling process is used to join or assemble the parts [1]. Burr is the major problem in the formation of holes in drilling process. Drilling was conducted on Al6061/10%/20%/Al_2O_3 composites with high speed drill bit. The results revealed that increase in thrust force increases the burr formation [2]. In this study, drilling process parameters like spindle speed, feed rate and weight percentage of SiC were optimized for burr height on Al356/SiC/mica hybrid composites. The result showed that burr height increases with increase in feed rate as well as with weight percentage of SiC particles and also decreases with increase in cutting speed [3]. The authors studied drilling of Al2024-T351 and Al7075-T6. The results indicated that low feed rate at exit and tooling design will minimize the burr size [4]. Drilling on AISI304L and AISI4118 was carried out using high speed steel split point twist drill bit. The result showed that burr size was governed by a combination of feed and speed related parameters, irrespective of drill diameter [5]. Drilling was conducted on Al2219/15%/SiC and Al2219/15%/SiC/3Gr hybrid composites to analyze the effect of spindle speed and feed rate on burr height. The result indicated that interaction of cutting speed and feed rate did not have any physical and statistical significance for both the materials. Also, burr height was increased with increase in feed rate and decreased with increase in cutting speed [6]. Optimal parameters were determined for selected drill diameters to minimize the burr height and burr thickness during drilling of AISI316L [7]. The authors investigated the performance of lubrication in drilling AA6063-T6 with high speed drill bit. The result showed that the drilling performance in terms of burr height had been improved in minimum quantity lubrication. A higher temperature, material becomes more deformable and leads to chip formation area, which influences the burr size [8]. The effects of change in step drill geometry on burr formation were analyzed. Carbide drill bits with 140^0 point angle were used for drilling SM45C alloy steel. It was observed that the step drill bit generated burr in small size as compared to a conventional drill bit [9]. Influence of process parameters such as cutting speed, feed, and use of cooling lubricants on drilling 16MnCr 5 and Ck45 was investigated. Investigation showed that burr value increases with increase in feed and decreases with increase in speed [10]. The authors reported the experi-

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mental investigations on reducing burr formation while drilling through-holes in metals. They identified optimal process conditions to minimize the sizes of burr at the entry and exit of holes. An attachment was developed on the principle of continuous modification of feed at the entry and exit of holes, which provide substantial reductions (30-40 percent) in the sizes of burrs in different materials like copper, aluminium, mild steel, stainless steel [11]. The authors investigated that addition of mica to Al356/SiC composite helps in reducing the burr height. When drilling Al356 /SiC-mica hybrid composite, at low feed rate, the thrust force encountered by the material is less and leads to reduced plastic deformation and burr height [12]. A special high speed steel drill bit is used to investigate the effect on burr height while drilling Al6061-T6 and SM45C. The results showed that larger point angle and a smaller corner radius of the cutting edge have minimized the burr height [13].

Drilling on AISI B-1112 was conducted using ½ inch spiral point and chisel-point drill bits. It was noted that the hole produced with the spiral-point drill was smooth, round, and showed no sign of erratic motion of the drill axis; whereas chisel-point drill showed a large amount of erratic motion of the drill axis. The amount of hole oversize was also affected by the centering action of the drill point. Also, it was concluded that holes produced with spiral-point drills are closer to the drill size than those produced with chisel-point drills [14]. Drilling was conducted on AA2024-T3 with 3/16 inch, high-speed twist drill bits. The results indicated that the use of a pilot hole produced a significant difference in hole quality in both hand and machine drilling. These differences were likely due to the reduction in material to be removed by the primary bit and to the path that the pilot hole provided for the primary bit. The use of a pilot hole improved hole quality [15]. The authors focused on the problem of minimizing the difference in the diameters of the hole in each material in a hybrid stack. Among the studied factors affecting the difference in the diameters of the hole (nominal diameter, type of drilling machine, nature of materials, feed rate, and spindle speed), only the nominal diameter does not show a significant influence on the value of the difference in the diameters. The feed rate has a strong effect on the difference in diameter, but cutting speed displayed a smaller influence than these factors [16]. The authors explained two types of vibration in drilling, low frequency vibrations and high frequency vibration (Chatter). They revealed that high frequency vibration is the most common cause for roundness problem in drilled holes. Authors also explained that low frequency vibration is significant for drilling because it directly affects hole quality [17]. The study investigated the influence of the factors on thrust force, diameter, and roundness deviations while drilling glass fiber reinforced epoxy resin with high speed steel and cemented carbide drills. The results indicated that the high speed steel drill presented severe wear after drilling 1000 holes, thus promoting high thrust force and roundness deviation values [18]. Taguchi method was used to optimize the surface finish and hole diameter accuracy in the dry drilling of Al2024 alloy. The parameters of hole quality were analyzed under varying cutting speeds, feed rates, depths of drilling, and drilling bits of HSS twist uncoated and TiN coated. This study concluded that depth of drilling and feed rate factors present statistical and physical significance on the hole diameter accuracy [19]. The authors explained that the changes in the relative motion of the drill affect the variations of the forces. An increase in the ranges of drill motion results in an increase in the ranges of torque and thrust. They suggested that drill vibrations can have an effect on drilling performance because increasing vibration during entry can cause poor hole location accuracy and burr formulation [20]. Experimental study investigated the influence of cutting speed, temperature, feed rate, geometrical parameters on hole quality while drilling aluminium alloy AA2024. The study reflected that rising of helix angle with a large point angle gives optimal drill geometry. It can also be concluded that with quite large cutting speed values and a weak feed rate leads to good surface quality and a dimensional accuracy of the holes [21].

Table 1. Chemical composition of aluminium alloy 6063.

Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Al
0.10	0.40	0.15	0.10	0.80	0.10	0.10	0.10	98.15

Burr may cause short circuits in electrical components, reduce the fatigue life of components, act as a crack initiation point. It may cause blockage of critical passages and turbulence in the flow of liquids or gases through conduits. This might cause serious problem. In case of parts moving relative to each other; friction and wear due to burrs not only reduce the edge quality but also produce noise and vibration.

To minimize above problems, step drill bits with different step angle were used. In this study, the optimization of cutting parameters on burr height and hole diameter in drilling process of Al6063/15%/SiC composites was investigated by using Taguchi method. Also we analyzed the results with the help of SEM and XRD analysis of composite, machining surface and drill bits.

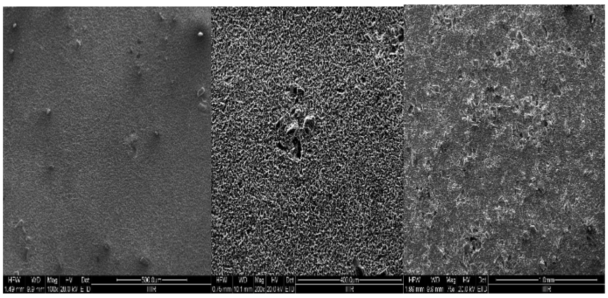
2. Materials and method

2.1 Materials

The aluminium alloy of 6xxx series has great potential in aero space engineering, automotive industry, electronic packaging and medical appliances because of its high strength to weight ratio and wear resistance. The composition of 6063 Al alloy is shown in Table 1.

Reinforcement SiC particulate form is used in the fabrication of composites. The size of reinforcement is 20-40 μm. Al6063/15%/SiC composite is fabricated using mechanical stir casting process at different stirring speed and stirring time. The microstructure of various composites is shown in Figs. 1(a)-(c) at different conditions.

Figs. 1(a) and (b) shows the non uniform microstructure at high and low stirring speed, respectively. At higher stirring



(a) (b) (c)

Fig. 1. Microstructure of the AA6063/15%/SiC composite with (a) stirring speed = 800 r.p.m and stirring time = 12 min; (b) stirring speed = 500 r.p.m and stirring time = 6 min; (c) stirring speed = 750 r.p.m and stirring time = 10 min.

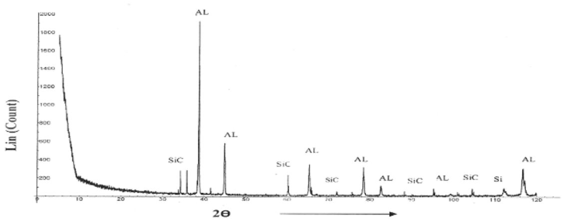


Fig. 2. XRD spectrum of AA6063/15%/SiC composite.

speed (800 rpm) particles are segregated. So they are not distributed uniformly in the matrix. At low stirring speed (500 rpm), particulate settled down at a particular place. Fig. 1(c) shows the uniform distribution of the SiC particle in the matrix at stirring speed of 750 rpm and stirring time 10 min.

The XRD analysis was carried out with Bruker AXS D8 ADVANCE diffractometer with Cu radiation at IIT Roorkee INDIA.

Fig. 2 shows XRD spectrum of Al6063/15%/SiC composites. There is no adverse effect, which means that Al_4C_3 is not formed during reaction.

3. Taguchi method

The Taguchi methodrefers to the technique of quality engineering. Taguchi's parameter design not only can reduce product cost, improve quality, but also reduce experimental time interval. In this study, the prediction of burr height and hole diameter error were selected as a quality characteristic to optimize the drilling parameters like cutting speed (A), feed rate (B), step angle (C) and cutting environment (D). L_{27} (3^{13}) orthogonal array is chosen due to its capability to check the interactions among the parameters. Parameters A, B, C, and D are arranged in columns 1, 2, 5, and 9, respectively, which are shown in Table 2. The S/N ratio was used to measure the quality characteristic deviating from the desired value. The signals are indicators of the effect on the average responses. The noises are measures of the influence on the deviations from the average responses, which accounts for the sensitiveness of the experiment output to the noise factors.

In this study, the S/N ratio was chosen according to the criterion the "smaller-the-better," in order to minimize the response. The S/N ratio of the "smaller-the-better" can be expressed as follows [21]:

Table 2. L_{27} (3^{13}) standard orthogonal array table with parameters A, B, C, D and their interactions [22].

Column trail	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	2	3	1	2	2	3	1
17	2	3	1	2	2	3	3	1	2	3	3	1	2
18	2	3	1	2	3	1	1	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right), \quad (1)$$

where n is the number of repetitions of the experiments and y_i is the average measured value of experimental data "I".

3.1 Analysis of variance (ANOVA)

ANOVA is a statistically based, objective decision-making tool for detecting any differences in average performance of groups of items tested. Analysis of variance is a method of portioning variability into identifiable sources of variation and the associated degree of freedom in an experiment [21]. The frequency test (F-test) is utilized to analyze the significant effects of the process parameters on the quality characteristics. ANOVA analysis was carried out for a level of significance. If

Table 3. Process parameters and their ranges.

Symbol	Factor	Level-1	Level-2	Level-3
A	Cutting speed (m/min)	37.68	103.62	150.72
B	Feed rate (mm/rev)	0.05	0.15	0.25
C	Step angle (Degree)	90	118	135
D	Cutting environment	Dry	Water soluble oil	Synthetic oil

Fig. 3. Experimental set up of CNC drilling machine.

(a) (b) (c)

Fig. 4. Photographs of step drills used for the investigations ((a) step angle 135°; (b) step angle 118°; (c) step angle 90°).

the calculated F-ratio is more than the tabulated value for a parameter at confidence level, then the effect is significant, and if it is less, then the factor is insignificant. The "Percent" contribution (P) of each factor was the total variation, indicating its influence on the result. MINITAB version 16 software was used to carry out statistical analysis involving analysis of variance (ANOVA) [23]. Based on the literature review and pilot experiments, the following process parameters and their ranges have been selected, which are shown in Table 3.

4. Experimental setup of CNC drilling machine

The experiments were on BFW 30 CNC VS three axis vertical machine center with 5.5 KW driver motor as shown in Fig. 3.

For generating the drilled holes, CNC part programs for tool paths were created with specific commands. The experimentation was done with three step twist drill bits (8 mm smaller, 12 mm larger diameter and 118^0 point angle) of HSS manufactured by Addison as shown in Fig. 4. The work piece is mounted on a machine table to provide maximum rigidity. It is parallel to the machine table and perpendicular to the machine's spindle head. The specimens of 300 mm × 25 mm × 25 mm rectangular section were used.

The burr height (BH) of each drilled hole was measured with a TRIMOS height gauge with least count 0.001mm. The values of burr size were recorded at three equally spaced locations around the circumference and average reading was taken as process response. The hole error of each drilled hole was measured with the aid of a Mitutoyo Crystal-Apex C (Japan) coordinate measuring machine (CMM). Hole diameter error (HDE) was taken at three positions spaced at 120° intervals around the hole circumference. In this experimental study, the hole diameter error was the arithmetic mean average, which is mostly used in the industry. The detailed sequences of parameters with response are shown in Table 4.

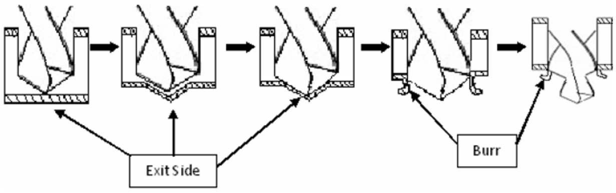
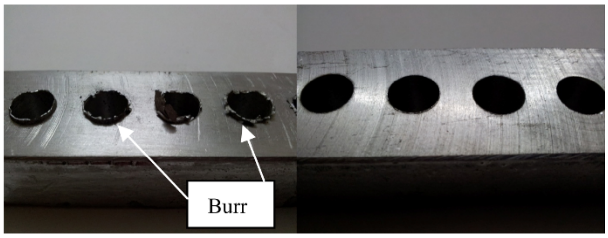


Fig. 5. Step procedure of burr formation.



(a) (b)

Fig. 6. Burr formation while drilling of AA6063/15%/SiC with (a) conventional drill bits; (b) step angle drill bit.

The steps of burr removal process are shown in Fig. 5. The figure shows that burr generated in the first step (at point cutting) of drilling is completely removed by the second cutting edge (at step angle). The basic cutting mechanism of step angle geometry is a reason of reduction of burr height.

Figs. 6(a) and (b) presents photographs of various holes in the Al6063/15%/SiC composite. Figs. 6(a) and (b) show that holes are drilled with conventional drill and step drill respectively. In step drill, burr height is smaller than the conventional drill.

5. Results and discussion

5.1 Burr height

The main effects and pooled ANOVA of burr height from raw data and S/N data are presented in Tables 5 and 6. In main effects and ANOVA response table, L1, L2 and L3 represent average value of data at level 1, 2 and 3, respectively. L2-L1 is the average main effect when the parameter changes from level 1 to level 2. L3-L2 is the average main effect when the parameter changes from level 2 to level 3. ANOVA analysis is preferred for a 5% ($P<0.05$) significant level, i.e., for 95% confidence level to identify the cutting parameters that affect

Table 4. Experimental results for step drill in AA6063/15%/SiC composites.

Trail no.	Factor				Measured parameters			S/N ratio	Measured parameters			S/N ratio
	A	B	C	D	BH 1	BH2	BH 3	S/N	HDE 1	HDE 2	HDE 3	S/N
1	37.68	0.05	90	Dry	0.148	0.141	0.146	16.729	0.02208	0.02198	0.02209	16.729
2	37.68	0.05	118	Water soluble	0.212	0.212	0.215	13.411	0.02269	0.02272	0.02275	13.411
3	37.68	0.05	135	Synthetic oil	0.282	0.275	0.277	11.106	0.02311	0.02315	0.02301	11.106
4	37.68	0.15	90	Water soluble	0.179	0.181	0.186	14.788	0.02223	0.02222	0.02218	14.788
5	37.68	0.15	118	Synthetic oil	0.231	0.231	0.231	12.703	0.02301	0.02292	0.0228	12.703
6	37.68	0.15	135	Dry	0.302	0.31	0.309	10.256	0.02349	0.02328	0.02346	10.256
7	37.68	0.25	90	Synthetic oil	0.316	0.312	0.314	10.059	0.02327	0.02328	0.02329	10.059
8	37.68	0.25	118	Dry	0.33	0.36	0.33	9.354	0.02466	0.02478	0.02484	9.354
9	37.68	0.25	135	Water soluble	0.38	0.38	0.38	8.404	0.0264	0.0261	0.0255	8.404
10	103.62	0.05	90	Dry	0.116	0.115	0.111	18.819	0.02131	0.02133	0.02147	18.819
11	103.62	0.05	118	Water soluble	0.159	0.157	0.161	15.924	0.02168	0.02175	0.02161	15.924
12	103.62	0.05	135	Synthetic oil	0.259	0.264	0.26	11.664	0.0222	0.02228	0.02221	11.664
13	103.62	0.15	90	Water soluble	0.15	0.15	0.15	16.466	0.02219	0.02232	0.02236	16.466
14	103.62	0.15	118	Synthetic oil	0.229	0.227	0.222	12.886	0.02282	0.02278	0.02277	12.886
15	103.62	0.15	135	Dry	0.278	0.286	0.288	10.919	0.02297	0.02303	0.02309	10.919
16	103.62	0.25	90	Synthetic oil	0.121	0.126	0.125	18.116	0.02321	0.02318	0.02309	18.116
17	103.62	0.25	118	Dry	0.231	0.231	0.231	12.708	0.02419	0.02411	0.02412	12.708
18	103.62	0.25	135	Water soluble	0.293	0.308	0.305	10.386	0.02475	0.02474	0.02479	10.386
19	150.72	0.05	90	Dry	0.081	0.085	0.086	21.432	0.01983	0.01977	0.01983	21.432
20	150.72	0.05	118	Water soluble	0.105	0.106	0.11	19.378	0.02068	0.02068	0.02071	19.378
21	150.72	0.05	135	Synthetic oil	0.131	0.136	0.138	17.364	0.02144	0.02144	0.02141	17.364
22	150.72	0.15	90	Water soluble	0.119	0.128	0.119	18.224	0.02215	0.02201	0.02217	18.224
23	150.72	0.15	118	Synthetic oil	0.214	0.215	0.216	13.342	0.023	0.02298	0.02293	13.342
24	150.72	0.15	135	Dry	0.291	0.295	0.29	10.672	0.02317	0.02315	0.02316	10.672
25	150.72	0.25	90	Synthetic oil	0.243	0.236	0.241	12.373	0.02328	0.02328	0.02328	12.373
26	150.72	0.25	118	Dry	0.294	0.295	0.293	10.629	0.02368	0.02366	0.02358	10.629
27	150.72	0.25	135	Water soluble	0.333	0.338	0.331	9.518	0.02405	0.02406	0.02401	9.518

Table 5. Main effects and pooled ANOVA data for burr height (Experimental data).

Main effects							Pooled ANOVA				
Source	L1	L2	L3	L2-L1	L3-L2	(L3-L2)- (L2-L1)	SS	DF	V	F-ratio	P%
A	0.2659	0.2061	0.2030	-0.059	-0.003	0.056	0.022	2	0.01131	17.55	11.85
B	0.1668	0.2237	0.2847	0.056	0.061	0.004	0.062	2	0.03129	48.55	34.06
C	0.1643	0.2245	0.2862	0.06	0.061	0.001	0.066	2	0.03341	51.85	36.43
D	0.2328	0.2170	0.2253	-0.015	0.008	0.024	0.001	2	0.00057	0.88	
AXB							0.019	4	0.00479	7.43	9.22
Error							0.003	6	0.00064		8.41
Total							0.179	26			100

Table 6. Main effects and Pooled ANOVA data for burr height (S/N data).

Main effects							Pooled ANOVA				
Source	L1	L2	L3	L2-L1	L3-L2	(L3-L2)-(L2-L1)	SS	DF	V	F-Ratio	P%
A	11.87	14.21	14.77	2.34	0.56	-1.78	42.676	2	21.338	15.507	11.86
B	16.2	13.36	11.28	-2.84	-2.08	0.76	109.798	2	54.899	39.897	31.79
C	16.33	13.37	11.14	-2.96	-2.23	0.73	122.06	2	61.03	44.353	35.43
D	13.5	14.06	13.29	0.56	-0.77	-1.33	2.81	2	1.405	1.021	
AXB							41.663	4	10.415	7.569	10.74
Error							8.256	6	1.376		10.18
Total							336.727	26			100

Table 7. Main effect and Pooled ANOVA data for hole diameter error (Experimental data).

Main effects							Pooled ANOVA				
Source	L1	L2	L3	L1-L2	L3-L2	(L3-L2)- (L2-L1)	SS	DF	V	F-ratio	P%
A	0.023	0.0228	0.022	-0.0005	-0.0004	7E-05	5E-06	2	2.5E-06	23.11	10.60
B	0.021	0.0227	0.024	0.0011	0.0013	0.00025	2.7E-05	2	1.35E-05	128.9	60.60
C	0.022	0.0229	0.023	0.0007	0.0005	-0.0002	8E-06	2	4E-06	35.86	17.42
D	0.022	0.0229	0.022	0.0001	-0.0001	-0.00029	0.0000	2	0.0000	0.58	
AXB							3E-06	4	7.5E-07	6.5	5.30
Error							1E-06	6	1.6E-07		6.06
Total							4.4E-05	26			100

Table 8. Main effect and Pooled ANOVA data for hole diameter error (S/N data).

Main effects							Pooled ANOVA				
Source	L1	L2	L3	L1-L2	L3-L2	(L3-L2)- (L2-L1)	SS	DF	V	F-ratio	P%
A	32.63	32.84	33.03	0.21	0.19	-0.02	0.71	2	0.35	27.98	10.88
B	33.29	32.86	32.36	-0.43	-0.5	-0.07	3.90	2	1.95	152.3	61.01
C	33.09	32.81	32.61	-0.28	-0.2	0.08	1.07	2	0.53	42.04	16.54
D	32.85	32.81	32.85	-0.04	0.04	0.08	0.01	2	0.00	0.45	
AXB							0.44	4	0.11	8.76	6.25
Error							0.07	6	0.012		5.30
Total							6.35	26			100

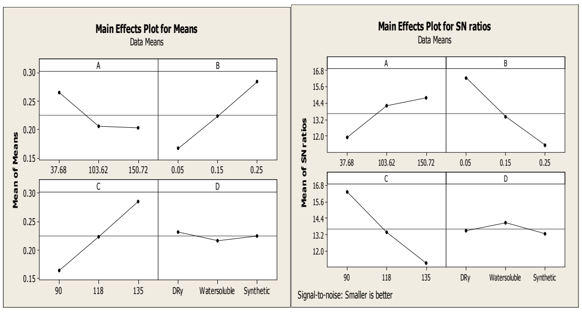


Fig. 7. Main effects plot of burr height for experimental data and S/N data.

the burr height. According to Table 5, step angles are found to be the major contribution (36.43%) and followed by feed rate (34.06%) and cutting speed (11.85%). Same rules follow for S/N ratio. The interaction of cutting speed and feed rate, i.e., A×B (9.22%) has only significant influence on burr height.

5.1.1 Influence of cutting speed on response

The mean response data of Tables 5 and 6 for burr height are plotted in Fig. 7. The figure shows the main effect of average values of cutting speed, feed rate, step angle and cutting environment conditions at level 1, 2 and 3 on burr height for experimental as well as S/N data.

Fig. 7(a) revels that the burr height decreases with increase in cutting speed. At low cutting speed, interfacial friction between drill bit and work piece generates heat and decreases the tool strength. Due to this, thrust force increases. At higher cutting speed, the cutting time decreases and results in to lower thrust force. So burr height decreases.

5.1.2 Influence of feed rate on response

Fig. 7(b) shows the effect of feed rate on burr height. The burr height increases with increase in feed rate. When feed rate increases, thrust force and chip thickness increases. This leads to increase the burr height. The larger amount of heat is generated at the chip tool interface. This heat increases the ductility of material. So, the thrust force bends the material to larger extent before interfacial bond cracking progress. This will result in larger burr height. The results indicate that lower feed rate is recommended in drilling AA 6063/15%/SiC composites.

5.1.3 Influence of step angle on response

Fig. 7(c) represents the effect of step angle on burr height. When step angle increases then burr height increases because of the lower stiffness of cutting edges. An increase in step angle, wider cutting edge and increases the area of cut. It will reduce the stiffness of cutting edge and increases the cutting resistance. Drilling with smaller step angle, the step edges keep sufficient stiffness up to the end of the edges and reduce the burr height. The results indicate that smaller step angle is recommended in drilling AA 6063/15%/SiC composites.

5.1.4 Influence of cutting environment on response

Fig. 7(d) indicates the effect of cutting environment on burr height. The magnitude differences in all three environmental conditions are very small. The main reason is that the oil used effectively works as coolant, but did not provide any lubricat-

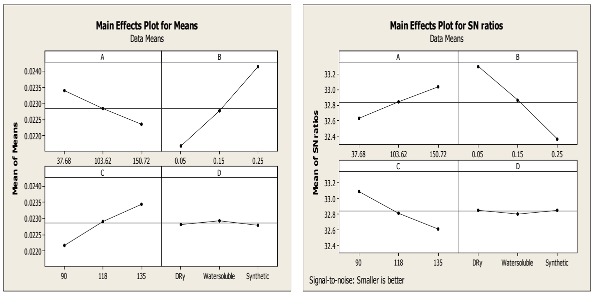


Fig. 8. Main effects plot of hole diameter error for experimental data and S/N data.

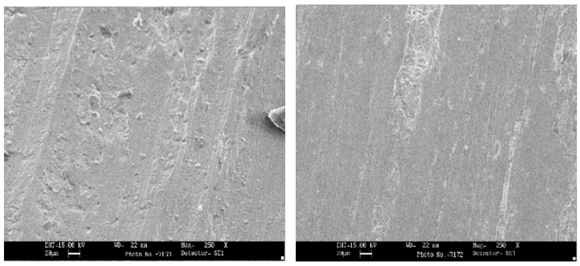
ing layer between tool and work piece. That's why cutting oil does not play any significant role in reducing the frictional resistance. It reveals that all three levels, i.e., dry, water soluble oil and synthetic oil do not show any significant impact on burr height.

5.2 Hole diameter error

Hole diameter error corresponds to a dimensional tolerance that controls how much a hole size deviates from perfect size. For the precision assembly of the parts, it is necessary that the hole generated should have minimum error. It is most important where error in dimension caused failure of human life. Tables 7 and 8 show the result of ANOVA for experimental data and calculated S/N for hole diameter error. Analysis of variance (ANOVA) gives valuable information regarding the significance of the factors and their interactions on the hole diameter error. The cutting speed, feed rate and step angle are the three significant factors which are shown in Table 7. Feed rate (60.60%) has highest percentage contribution and followed by step angle (17.42%) and cutting speed (10.60%). Similarly for S/N ratio, cutting speed (10.88%), feed rate (61.01%) and step angle (16.54%) are the significant parameters for hole diameter error. The interaction of cutting speed and feed rate, A×B (6.25%), has only significant influence on hole diameter error.

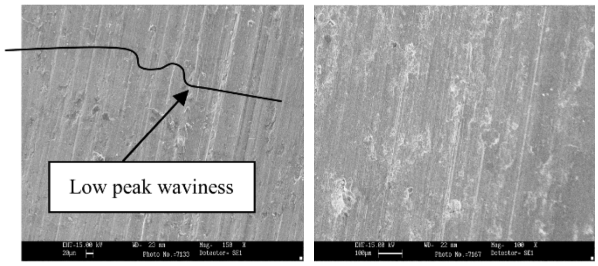
Fig. 8(a) represents the effect of cutting speed on hole diameter error. When the cutting speed increases, hole diameter error decreases. At higher cutting speed, interfacial friction duration decreases. This reveals a decrease in thrust force, which causes chattering. Fig. 8(b) indicates the effect of feed rate on hole diameter error. Hole diameter error increases with increases in feed rate. This is due to higher thrust force required for thick chips. Fig. 8(c) shows the effect of step angle on hole diameter error. An increase in step angle increases hole diameter error. Increase in step angle, wider the cutting edge.

Wider edges require higher thrust force to penetrate inside composite, thus increasing vibrations which increases the hole diameter error. Also due to step geometry, it holds and guides drills through pilot hole. This will reduce the vibrations and decrease the hole diameter error. Fig. 8(d) reflects the effect of cutting environment on hole diameter error, indicating that all three environmental conditions have small magnitude differences. It shows that all three levels do not show any significant impact on hole diameter error.



(a) (b)

Fig. 9. SEM photograph illustrating the drilled surface at a cutting speed 150.72 m/min, step angle 90^0 and feed rate for (a) 0.25 mm/rev; (b) 0.05 mm/rev.



(a) (b)

Fig. 10. SEM photograph illustrating the drilled surface at a cutting speed 150.72 m/min, feed rate 0.05 mm/rev and step angle for (a) 135^0; (b) 90^0.

The SEM analysis of drilled surface is presented in Figs. 9 and 10 at different cutting conditions. Keen evaluation of SEM photographs in Fig. 9(a) reflects high peak waviness. This waviness reflects high thrust force. This thrust force is attributed to chattering effect (high frequency vibrations) and generates uneven surface. It is also observed from Fig. 9(b) that lower feed rate has a good surface finish. This reflects the least hole diameter error. Figs. 9(a) and (b) represent the value of hole diameter error is 0.02328 mm and 0.01981 mm. Figs. 10(a) and (b), presents the effect of step angle on hole diameter error. Fig. 10(a) consists of low peak waviness. This is due to resistance of cutting edges at higher step angle. This decreases the tool strength and results in a rough surface. The absence of waviness in Fig. 10(b) reflects the lower hole diameter error. The measured value of hole diameter error for Figs. 10(a) and (b) is 0.01981mm and 0.02143. This analysis also supports ANOVA results, that feed rate has dominant effect on hole diameter error and followed by step angle.

6. Optimization of burr height and hole diameter error

6.1 Predicting the optimum performance

The optimum value of burr height and hole diameter error is predicted at selected levels of significant process parameters.

Table 9. Optimum levels of process parameters for burr height and hole diameter error.

Process parameter	Burr height		Hole diameter error	
	Parameter designation	Optimum level	Parameter designation	Optimum level
Cutting speed (m/min.)	A_3	150.72	A_3	150.72
Feed rate (rev/mm)	B_1	0.05	B_1	0.05
Step angle (Degree)	C_1	90	C_1	90
Cutting environment	D_2	Water soluble oil	D_3	Synthetic oil

The significant process parameters and their optimum levels have been already selected and tabulated in Table 9. After the optimal level has been selected, one could predict the optimum response (burr height and hole diameter error) using the following equation [21]:

$$\mu_{predicted} = \mu_m + \sum_{i=1}^{n} \left(\mu_o - \mu_m\right) , \quad (2)$$

where μ_m is the overall mean response or mean S/N ratio, μ_o is the mean response or mean S/N ratio at optimal level, and *n* is the number of main design parameters that affect the quality characteristics. It is very essential to perform a confirmation experiment for the parameter design, particularly when fewer numbers of data are utilized for optimization. The purpose of this confirmation experiment is to verify the improvement in the quality characteristics.

6.1.1 Burr height

Using Eq. (2), predicted mean of response characteristic (burr height) can be calculated as

$\mu_{Burr\ height} = A_3 + B_1 + C_1 - 2T = 0.084$ mm.

The 95% confidence interval of confirmation experiment (Cl_{CE}) was calculated by following equation [15]:

$$Cl_{CE} = \sqrt{F_x\left(1, f_e\right)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]}, \quad (3)$$

$$Cl_{POP} = \sqrt{\frac{F_x\left(1, f_e\right)V_e}{n_{eff}}}, \quad (4)$$

where Ve is the error variance, Fα (1, fe) is the F-ratio at a confidence level of (1-α) against DOF, 1 and error degree of freedom fe .α is confidence level [21].

n_{eff} = N/1+[Total DOF associated in estimate of mean]

where N is the total number of results = 81 and R is the sample size for confirmation experiment = 3.

n_{eff} = 11.571.

Error variance V_e = 0.0006 (Table 5), f_e= error DOF= 6 (Table 5). F (1, 6) = 5.14 (Tabulated F-ratio) [21].

So $CL_{CE} = \pm 0.036$.

Predicted optimum range for confirmation experiment is:

Predicted burr height + CI_{CE}> Burr height > Predicted burr height - CI_{CE}

0.084+0.036 > Burr height > 0.084-0.036

0.12 > Burr height > 0.048.

Similarly, population is

$Cl_{POP} = \pm 0.016$.

The 95% confidence interval of the predicted mean is:

Predicted burr height + CI_{POP} > Burr height > Predicted burr height - CI_{POP}

0.0841+0.016 > Burr height > 0.0841-0.016

0.1001>Burr height >0.0681.

6.1.2 Hole diameter error

Similarly, Cl_{CE} and CI_{POP} of hole diameter error (HDE) was calculated using Eqs. (3) and (4).

$CL_{CE} = \pm 0.0006$

Predicted hole diameter error + CICE> HDE > Predicted hole diameter error - CICE

0.0211>HDE > 0.0199

$Cl_{POP} = \pm 0.00027$.

Predicted hole diameter error + CI_{POP}> HDE > Predicted hole diameter error - CI_{POP}

0.02077> HDE > 0.2023.

6.2 Verification of optimal parameters through confirmation test

The confirmation experiments were conducted at the optimum level of process parameters. The cutting speed was at third level (A_3), feed rate at first level (B_1), step angle at third level (C_1) and cutting environment at second level (D_2). Using these parameters, drilling was conducted and the average experimental value was 0.0787 mm for burr height. Similarly, using optimum level A_3, B1, C_1 and D_3 the average hole diameter error was 0.0205mm. These values are within the confidence interval of predicted optimal of burr height and hole diameter error.

7. Sem analysis of step drill bits

Fig. 11(a) shows that the drill bit with higher step angle (135^0) is highly affected compared to drill with lower step angle.

Fig. 11(a) shows adhesion of matrix material, wear and pits

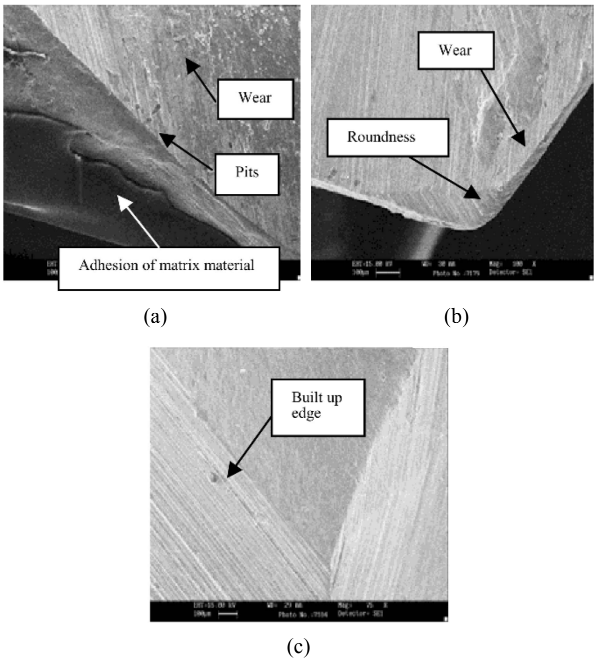


Fig. 11. SEM photograph illustrating the drill bits at a cutting speed of 150.72 m/min and feed rate of 0.05mm/rev for (a) 135°; (b) 118°; (c) 90° step angle.

on drill bit. This will decrease the tool strength. Fig. 11(b) indicates wear and roundness of edges on drill bit having 118^0 step angle. Fig. 11(c) shows that least effect on drill having 90^0 step angle. Figs. 11(a)-(c) shows a major change in 135^0 step angle drill bit. The reason is high thrust force and frictional resistance of cutting edges at higher step angle. This increases cutting temperature at chip tool interface. This will contribute to drill wear, adhesion, built up edges and generate a hole with waviness surface and burr. The above analysis also supports our results.

8. Conclusions

An Al6063/15% vol. SiC composite was drilled with high speed steel (HSS) single step drill bits. The results indicated that the drilling-tool geometry plays a significant role in the drilling of aluminum matrix composites. The following conclusions are drawn from above analysis:

(1) Cutting speed, feed rate, step angle and the interaction between cutting speed and feed rate are the significant parameters for burr height and hole diameter error.

(2) Increase in feed rate and step angle, increased burr height and hole diameter error and increase in cutting speed decreases burr height and hole diameter error.

(3) In burr height, the significant contribution of cutting speed (A), feed rate (B), step angle (C), and interaction (A×B) are 11.86%, 31.79%, 35.43%, and 10.74% respectively.

(4) In hole diameter error, the significant contribution of cutting speed (A), feed rate (B), step angle (C), and interaction (A×B) are 10.88%, 61.01%, 16.54%, and 6.25% respectively.

(5) The optimum parameters for minimize burr height and hole diameter error are cutting speed of 150.72 m/min, feed rate of 0.05 mm/rev, step angle of 90^0 and cutting environment of water soluble oil .

(6) The 95% confidence intervals of the predicted mean for burr height and hole diameter error are: 0.12 > Burr height > 0.048 and 0.0211 > Hole diameter error > 0.0199 respectively.

(7) The SEM images of the drilled surfaces show the evidence of waviness, which causes for hole diameter error.

(8) Drill bit with higher step angle is highly affected according to the SEM analysis.

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