Engineering Science and Technology, an International Journal 19 (2016) 1199–1205

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Contents lists available at ScienceDirect

Engineering Science and Technology,
an International Journal

journal homepage: http://www.elsevier.com/locate/jestch

Full Length Article

Modeling of burr size in drilling of aluminum silicon carbide composites using response surface methodology

Avinash A. Thakre *, Shashank Soni

Department of Mechanical Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India

A R T I C L E I N F O

Article history:
Received 26 October 2015
Received in revised form
22 February 2016
Accepted 23 February 2016
Available online 24 March 2016

Keywords:
Drilling process
Metal matrix composite
Burr height
Burr thickness
Response surface methodology

A B S T R A C T

Exit burrs produced during various machining processes degrade the product quality and functionality of different parts of assembly. It is essential to select the optimum tool geometry and process parameters for minimizing the burr formation during machining. In this paper, the effects of cutting speed, feed rate, point angle of drill bits and concentration of the reinforcements on the burrs produced were investigated. Response surface methodology has been adopted to create the quadratic model for the height and thickness of the burrs produced during drilling of Al—SiC composites. Analysis of means and variance were used to find the significance of the process parameters on the responses and to find the optimum combination of parameters to minimize the burr formation. Feed rate, point angle and concentration of reinforcements in the matrix are found to be the significant factors. Both the responses were found to be minimum for lower feed rate, higher point angle and higher concentration of reinforcements. Scanning electron microscopy was used to understand the mechanism of burr formation.

1. Introduction

Drilling is the most basic conventional machining operation that is used for creating cavities or holes for the assembly of different parts. At production stage, during drilling operations, an uncut portion of material comes out along circumference of hole. This deposition of material at entry and exit of hole is called burr. The formation of burrs creates several problems like degradation in quality and performance of precision parts etc. It is estimated that approximately 20–30% of the manufacturing cost of the finished products is required for deburring process [1]. When exit burrs are formed inside a cavity, specialized tools are required for deburring them. Hence it is essential to minimize the burr formation during drilling process. This will reduce the extra time and cost required for deburring and will ensure the quality of precision parts.

In recent times, metal matrix composites (MMCs), especially particle reinforced aluminum matrix composites, have received considerable attention in automobile and aerospace industries. Conventional materials are replaced by metal matrix composites because of high strength to weight ratio, high-specific modulus, very high resonance frequency and other excellent mechanical properties. However the presence of abrasive particles as reinforcements in metal matrix composites makes drilling extremely difficult and requires special tooling. The formation of burrs at the entry and exit of hole is a common problem when drilling these composites. The presence of brittle reinforcements and ductile matrix makes the understanding of the mechanism of burr formation extremely interesting.

Researchers have tried to understand the mechanism of burr formation in metal matrix composites. Effects of various machining parameters such as cutting speed, feed rate [1–17], and cutting environment [8] on the burr formation during drilling are studied in detail. Also the effects of drill size and geometry such as drill type [9–13], drill diameters [2,3], point angle [1,2,4–7], step angle [8,9] and lip clearance angle [1,6] on the burr sizes are also studied. The type of burrs produced during drilling of metal matrix composites is also found to be dependent on the type of reinforcements [5], volume fraction of reinforcements [5,12–15] and presence of any solid lubricants such as graphite [10,16]. In case of metal matrix composites with the brittle reinforcements, irregular and crown shape burrs are formed [7]. The cracks are developed at the site of reinforcements and solid lubricants during debonding and propagate along feed direction. These cracks restrict or slow down the flow of material due to plastic deformation toward feed direction. Hence lower burr height and thickness are reported for higher fiber concentration in metal matrix composites [10,16]. Higher feed rate increases the thrust forces and pushes the material out of the work piece rather than cutting it [16]. At a larger point angle, drill bit exerts tensile stresses on the work piece hence smaller burrs are formed

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* Corresponding author. Tel.: +91 7122801236, fax: +91 7122802200.
E-mail address: avinashathakre@gmail.com (A.A. Thakre).
Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2016.02.007
2215-0986/

as the work piece material is more prone to cut than simply flow out of the surface [3,6,7]. Presence of solid lubricants in metal matrix composites sharply reduces thrust forces and results in smaller burrs [10,16].

The mathematical models have been suggested for the dimensions of the burrs produced during drilling process. A mathematical tool such as response surface methodology is a really efficient and useful tool for studying the effect of various parameters on the responses when compared to studying the effect of one variable at a time. Hence researchers preferred response surface methodology [3,7,18] for developing the mathematical model for the burr dimensions. Also other soft computing tools such as Taguchi technique [1,4,5,7,8,10,11,17], genetic algorithm [6] etc. are used for the optimization of height and thickness of burrs produced during drilling. For the optimization of multiple responses for machining processes Taguchi method can be coupled with Utility Concept [19], Grey Fuzzy Logic [20] and Principal Component analysis [21].

The formation of burrs while drilling of metal matrix composites is a serious issue and bottleneck in manufacturing process, which increases cost of manufacturing. In the current work effects of cutting parameters such cutting speed and feed rate on the height and thickness of the burrs produced during drilling of Al—SiC composites are studied in detail. Also the point angle of the drill bit and concentration of reinforcements are also selected as parameters to study the effect of tool geometry and work piece composition on the responses. Response surface methodology is employed to create a quadratic model for the burr dimensions. Analysis of variance (ANOVA) is employed to find the most significant parameters affecting the burr formation. The optimal combination of process parameters is identified to minimize the responses. The mechanism of burr formation in Al—SiC composites is studied using Scanning electron microscopy.

2. Material and method of analysis

2.1. Selection of materials

The matrix material used for these composites was aluminum 6061 alloy. Al6061 and Al6061-SiC plates of dimension 60 × 60 × 10 mm^3 were used for drilling experiments. Its chemical composition is shown in Table 1. This metal matrix composites are widely used in aerospace applications and microelectronics such as high performance electronic packaging and as a substrate for power semiconductors. Average size of silicon carbide particles used as reinforcements was 2–3 µm. The weight percentages of the reinforcements selected for the fabrication of the composites were 15% and 30%.

2.2. Methods of analysis

Response surface methodology is a powerful statistical tool for mathematical modeling of engineering systems and for optimization of the process parameters. The steps of this process start with the identification of the control parameters and their domain under consideration. The next step is to select the orthogonal design and to conduct the experiments based on this design. Then the empirical models are developed between the response and the process variables. The effects of various variables and their interactions on the response are studied. The accuracy and adequacy of the developed model is checked using statistical tools such as analysis of means and analysis of variances.

Table 1
Chemical composition of Al6061 alloy.

Mg	Si	Cu	Fe	Ti	V	Mn	Zn	Cr	Zr	Ni
0.766	0.354	0.214	0.132	0.019	0.011	0.029	0.085	0.166	0.024	0.012

Table 2
Machining factors and their levels.

Factors	Code	Levels		
		–1	0	1
Cutting speed (m/min)	A	40	60	80
Feed rate (mm/rev)	B	0.1	0.15	0.2
Concentration of reinforcements (%)	C	0	15	30
Point angle (degrees)	D	96	118	140

2.3. Experimental details

Drilling operations were performed on a computer numerical control vertical machining center 'Jyoti, VMC850' with Siemen Sinumerik 828D controller. Solid carbide drills (manufactured by SANDVIK) having 10 mm in diameter and three different point angles 96°, 118° and 140° were used. In the present study, four parameters were selected for the modeling of burr height and thickness. Table 2 indicates factors and their levels selected for the study. Box–Behnken design with L_{27} orthogonal array is used for the experimentation. The experiments were conducted in random fashion. Table 3 indicates the experimental design, height and thickness of burrs produced during drilling of these. Fig. 1 indicates the schematic diagram of irregular burrs, burr height (B_h) and burr thickness (B_t). After drilling the work piece, burr height for each drilled hole was measured by Coordinate Measuring Machine 'Mitutoyo Crystal-Apex C' at four positions spaced at 90° around the circumference of hole. The thickness of burrs produced was measured at four positions using Digital Microscope 'ISM-PM 200SB'. Then average values of the height and thickness of burrs were used for the modeling using response surface methodology.

3. Results and discussion

Response surface methodology is employed to develop the mathematical model for height and thickness of burrs produced in terms of cutting speed, feed rate, point angle and concentration of reinforcements. The second order non-linear model with linear, quadratic and interactive terms is indicated by Equation (1).

$$\begin{aligned} y = {} & \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_1^2 + \beta_6 x_2^2 + \beta_7 x_3^2 + \beta_8 x_4^2 \\ & + \beta_9 x_1 x_2 + \beta_{10} x_1 x_3 + \beta_{11} x_1 x_4 + \beta_{12} x_2 x_3 + \beta_{13} x_2 x_4 + \beta_{14} x_3 x_3 \end{aligned} \tag{1}$$

The values of regression coefficients (β_0, β_1, ——, β_{14}) were determined using Minitab software (Minitab, Inc., MINITAB release 16, 2012). The analysis was done using coded units. Tables 4 and 5 indicate the results of ANOVA for both the responses. The goodness of fit of the regression model was determined by calculating R^2 coefficient, which provides a measure of how much variability in the observed response can be explained by the model. R^2 value of 91% signified that 91% of the variation in the observed values of burr height could be explained by the model while only 9% of the total variations in the response values could not be explained by the model. Higher R^2 values (approximately 91% and 89% for the burr height and thickness) indicate that the model is accurate. Also the significance of regression model can be evaluated by F and P values. The F value predicts the quality of the entire model considering all design factors at a time. The P value is the probability of the factors having very little or insignificant effect on the response. Larger F value signifies better fit of the regression model with the experimental data. The calculated values of F-ratio for models of burr height and thickness are found to be 7.84 and 6.93, higher than the standard tabulated values of F-ratio. Higher F value with low P value (below 0.05) indicates high significance of the regression model. The

Table 3
Height and thickness of the burrs produced for various experimental combinations.

Run no.	Parameters				Burr height (mm)				Average burr height (mm)	Burr thickness (mm)				Average burr thickness (mm)
	A	B	C	D	1	2	3	4		1	2	3	4	
1	–1	–1	0	0	0.84	0.589	1.134	0.997	0.890	0.2807	0.3056	0.335	0.1626	0.2709
2	1	–1	0	0	0.91	1.22	0.34	1.654	1.031	0.2708	0.2941	0.1915	0.3427	0.2747
3	–1	1	0	0	1.084	1.42	1.056	1.072	1.158	0.3212	0.3000	0.2895	0.2368	0.2868
4	1	1	0	0	1.684	2.8	0.846	0.99	1.580	0.4232	0.3264	0.2867	0.2252	0.3153
5	0	0	–1	–1	2.58	2.02	1.416	1.924	1.985	0.5263	0.4308	0.5714	0.1607	0.4223
6	0	0	1	–1	1.38	0.873	0.907	1.208	1.092	0.2807	0.2244	0.3108	0.1373	0.2383
7	0	0	–1	1	0.712	1.172	0.98	0.42	0.821	0.3322	0.2210	0.1568	0.2372	0.2368
8	0	0	1	1	1.14	0.668	1.238	0.23	0.819	0.2924	0.1723	0.2096	0.2485	0.2307
9	–1	0	0	–1	1.06	1.36	0.84	1.1	1.091	0.2896	0.3570	0.3094	0.2661	0.3055
10	1	0	0	–1	2.66	1.36	1.836	1.377	1.808	0.4342	0.2822	0.2771	0.3153	0.3272
11	–1	0	0	1	1.293	0.825	1.9	1.578	1.399	0.3201	0.2616	0.2949	0.3474	0.3060
12	1	0	0	1	1.85	1.204	0.41	1.04	1.126	0.2239	0.2711	0.3627	0.3331	0.2977
13	0	–1	–1	0	0.52	1.273	0.69	0.985	0.867	0.2703	0.3281	0.289	0.2818	0.2923
14	0	1	–1	0	1.386	1.109	0.675	1.166	1.084	0.2372	0.2763	0.2205	0.2816	0.2539
15	0	–1	1	0	0.36	0.937	0.493	0.57	0.590	0.2236	0.2697	0.1294	0.1933	0.2040
16	0	1	1	0	1.03	1.15	1.374	0.571	1.031	0.3057	0.2847	0.2963	0.2498	0.2841
17	–1	0	–1	0	0.62	1.089	1.608	0.627	0.986	0.3254	0.3315	0.1561	0.2182	0.2578
18	1	0	–1	0	2.221	1.947	1.22	2.42	1.952	0.3534	0.3346	0.4593	0.3975	0.3862
19	–1	0	1	0	0.76	0.268	1.08	1.540	0.912	0.2525	0.3281	0.2863	0.1827	0.2624
20	1	0	1	0	0.43	1.245	0.933	0.892	0.875	0.2576	0.204	0.2203	0.1961	0.2195
21	0	–1	0	–1	0.623	0.79	0.892	1.591	0.974	0.4240	0.2162	0.3598	0.2293	0.3073
22	0	1	0	–1	1.63	1.763	0.856	2.703	1.738	0.3670	0.3037	0.2575	0.3422	0.3176
23	0	–1	0	1	0.075	0.35	0.79	0.11	0.331	0.1896	0.1579	0.1481	0.1684	0.1661
24	0	1	0	1	1.643	1.115	1.48	0.702	1.235	0.3068	0.2786	0.2396	0.3234	0.2871
25	0	0	0	0	0.65	0.22	0.87	1.1	0.710	0.2473	0.2047	0.1814	0.1747	0.2020
26	0	0	0	0	0.628	1.034	0.58	0.438	0.673	0.1694	0.2215	0.1743	0.1913	0.1891
27	0	0	0	0	0.625	0.813	0.71	0.972	0.780	0.2474	0.2692	0.2031	0.1843	0.2260

factors indicating P values higher than 0.05 indicate insignificant factors. Table 4 indicates that all the factors are significant for the burr height. However for the burr thickness only cutting speed is the insignificant factor as indicated in Table 5. Significant factors are labeled in the ANOVA results. Remaining insignificant linear, square and interactive terms were removed from the model. The final mathematical model for the burr height (B_h) and thickness (B_t) in terms of significant factors are indicated by Equations (2) and (3) respectively,

$$B_h = 0.720 + 0.1614A + 0.2619B - 0.1980C - 0.24636D + 0.3503A^2 + 0.3017D^2 - 0.2507AC - 0.2479AD + 0.22275CD \tag{2}$$

$$B_t = 0.2057 + 0.019125B - 0.0341C - 0.03281D + 0.054629A^2 + 0.02691C^2 + 0.032817D^2 - 0.042825AC + 0.0444CD \tag{3}$$

Figs. 2 and 3 indicate the main effect plots for both the height and the thickness of the burrs respectively. Feed rate, point angle and concentration of reinforcements are found to be significant factors. Minimum burr height and thickness are obtained for 60 m/min cutting speed, 0.1 mm/rev feed rate and 140° point angle for 30% concentration of SiC reinforcements in matrix. Burr height and thickness are found to be increasing approximately by 25–50% with the increase in feed rate from 0.1 to 0.2 mm/revolution. This indicates that the lower feed is required for the minimum burr size. Higher feed rate increases the thrust force while drilling the composites. Increase in thrust force tends to deform the soft aluminum matrix to a larger extent. This will avoid or delay the rupture of interfacial bonds between matrix alloy and SiC reinforcements. In the absence of any significant cracks induced by debonding of reinforcements and yielding of the matrix, the work piece material is more prone to flow out of the surface than cutting. This increases the height and thickness of the burrs produced during drilling of these composites [7,16].

The burr height and thickness reduced approximately by 25–40% for the increase in point angle from 96° to 118° and reduced

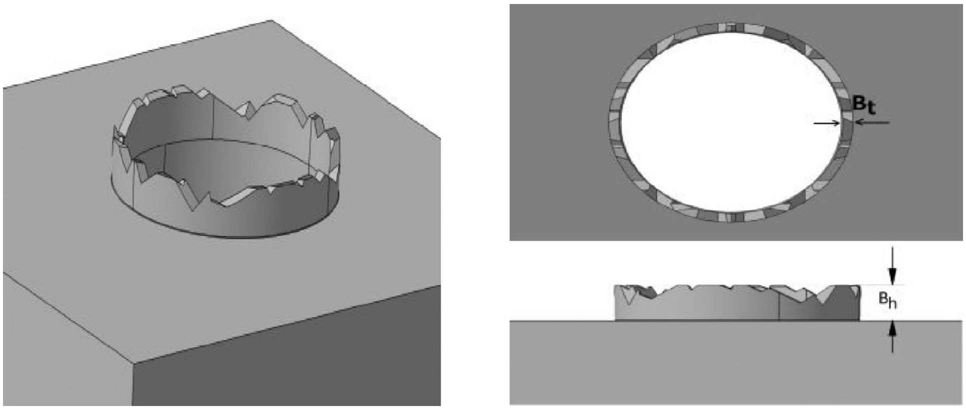

Fig. 1. Schematic diagram of irregular burrs produced during drilling.

Table 4
ANOVA results for burr height.

Source	Sum of square	DOF	Mean square	F-value	P-value	
Model	3.99342	14	0.285244	7.84	0.000	Significant
A – Cutting speed	0.31286	1	0.312864	8.6	0.013	Significant
B – Feed rate	0.82307	1	0.823073	22.63	0.000	Significant
C – Concentration of reinforcement	0.47045	1	0.470448	12.94	0.004	Significant
D – Point angle	0.72834	1	0.728344	20.03	0.001	Significant
A^2	0.42387	1	0.654577	18	0.001	Significant
B^2	0.01235	1	0.021193	0.58	0.46	
C^2	0.00392	1	0.084847	2.33	0.153	
D^2	0.48558	1	0.485581	13.35	0.003	Significant
AB	0.01974	1	0.01974	0.54	0.475	
AC	0.2515	1	0.251502	6.92	0.022	Significant
AD	0.24583	1	0.245828	6.76	0.023	Significant
BC	0.01254	1	0.012544	0.34	0.568	
BD	0.00488	1	0.004883	0.13	0.72	
CD	0.19847	1	0.19847	5.46	0.038	Significant
Residual	0.43641	12	0.03636			
Total	4.42982	26				

DOF, degree of freedom; F, Fischer; P, probability.

Table 5
ANOVA results for burr thickness.

Source	Sum of square	DOF	Mean square	F-value	P-value	
Model	0.07442	14	0.005403	6.93	0.001	Significant
A – cutting speed	0.001434	1	0.001434	1.84	0.2	
B – feed rate	0.004389	1	0.004389	5.63	0.035	Significant
C – concentration of reinforcement	0.014029	1	0.014029	18	0.001	Significant
D – point angle	0.012923	1	0.012923	16.58	0.002	Significant
A^2	0.00832	1	0.015917	20.42	0.001	Significant
B^2	0.000167	1	0.002918	3.74	0.077	
C^2	0.000796	1	0.003864	4.96	0.046	Significant
D^2	0.011386	1	0.011386	14.61	0.002	Significant
AB	0.000153	1	0.000153	0.2	0.666	
AC	0.007336	1	0.007336	9.41	0.01	Significant
AD	0.000225	1	0.000225	0.29	0.601	
BC	0.003511	1	0.003511	4.5	0.055	
BD	0.003064	1	0.003064	3.93	0.071	
CD	0.007912	1	0.007912	10.15	0.008	Significant
Residual	0.009353	12	0.000779			
Total	0.084997	26				

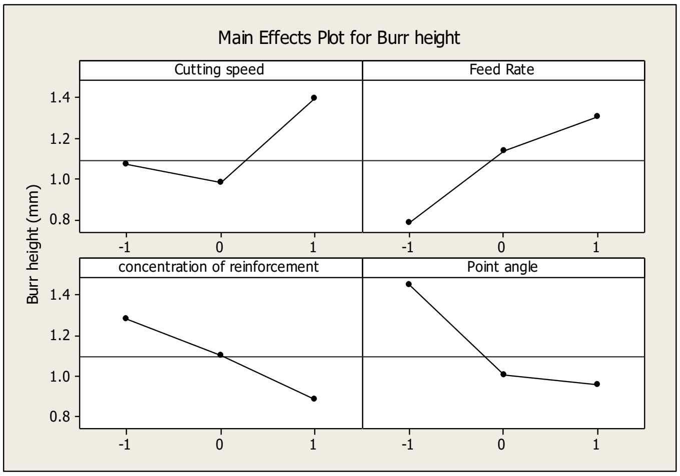

Fig. 2. Main effect plots for burr height.

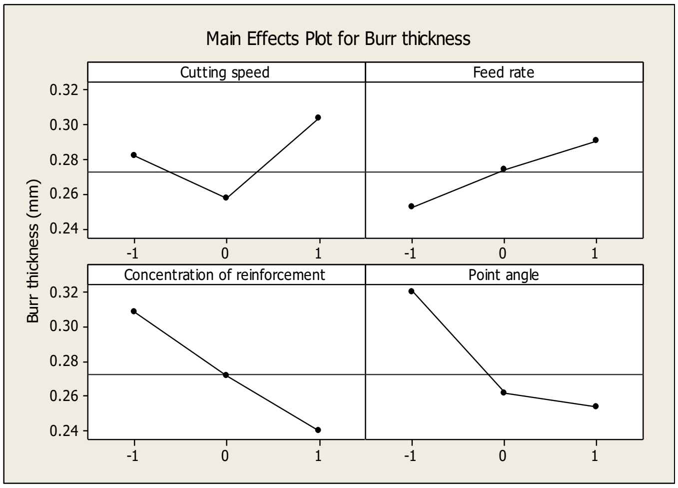

Fig. 3. Main effect plots for burr thickness.

marginally thereafter up to 140° point angle. This indicates that higher point angle is desirable for minimizing the burrs produced during drilling of Al—SiC composites. The higher point angle ensures maximum lip movement in earliest possible time to avoid strain hardening and results in change in chip flow direction resulting in smaller burrs [6,7]. Also the work piece material is more prone to cut rather than simply flow toward feed direction due to the tensile stresses exerted by drill bit with higher point angles. In the presence of these tensile stresses significant micro cracks will be developed from various debonding sites of reinforcements. These cracks will propagate and widen along the feed direction resulting into irregular burrs. It will restrict or slow down the yielding and flow of workpiece material toward feed direction. Hence smaller height and thickness of the burrs produced during drilling of Al—SiC composites are reported for a higher point angle [3,7].

Smaller burrs were formed in case of Al—SiC composites as compared to the aluminum alloy. Ductile materials tend to undergo higher plastic deformation and flow toward feed direction. Hence thick and bigger uniform burrs were formed in aluminum alloy [7]. However in case of abrasive SiC reinforcements, material tends to behave as brittle and produces irregular burrs. During drilling operation when lip area encounters abrasive SiC reinforcements, the micro-cracks are generated before the debonding of reinforcements from the matrix. These micro-cracks, which developed from various debonding sites, get broader while propagating toward feed direction. During curling of burrs at the exit of hole, the networking of these micro-cracks results in formation and detachment of independent regions of material. Hence burrs produced in Al—SiC composites are irregular having several lobes or petals [7]. With the increase in concentration of SiC reinforcement in aluminum matrix, the presence of higher debonding sites will lead to more significant networking of micro cracks and larger detachment of material from the burr. Hence approximately 15% and 30% reduction in the height and thickness of the burrs is achieved for the addition of 15% and 30% reinforcement respectively in Al—SiC composites.

Cutting speed is found to be a relatively less significant factor, although height and thickness of the burrs produced are found to be more for higher cutting speed. At higher cutting speed more heat is generated at the interface between the tool and work piece. This will increase the plasticity of aluminum alloy and it will flow easily toward the feed direction. Softening of matrix will reduce the debonding of reinforcement and reduce the formation of significant micro-cracks in the burrs [6]. Hence burr dimension are found

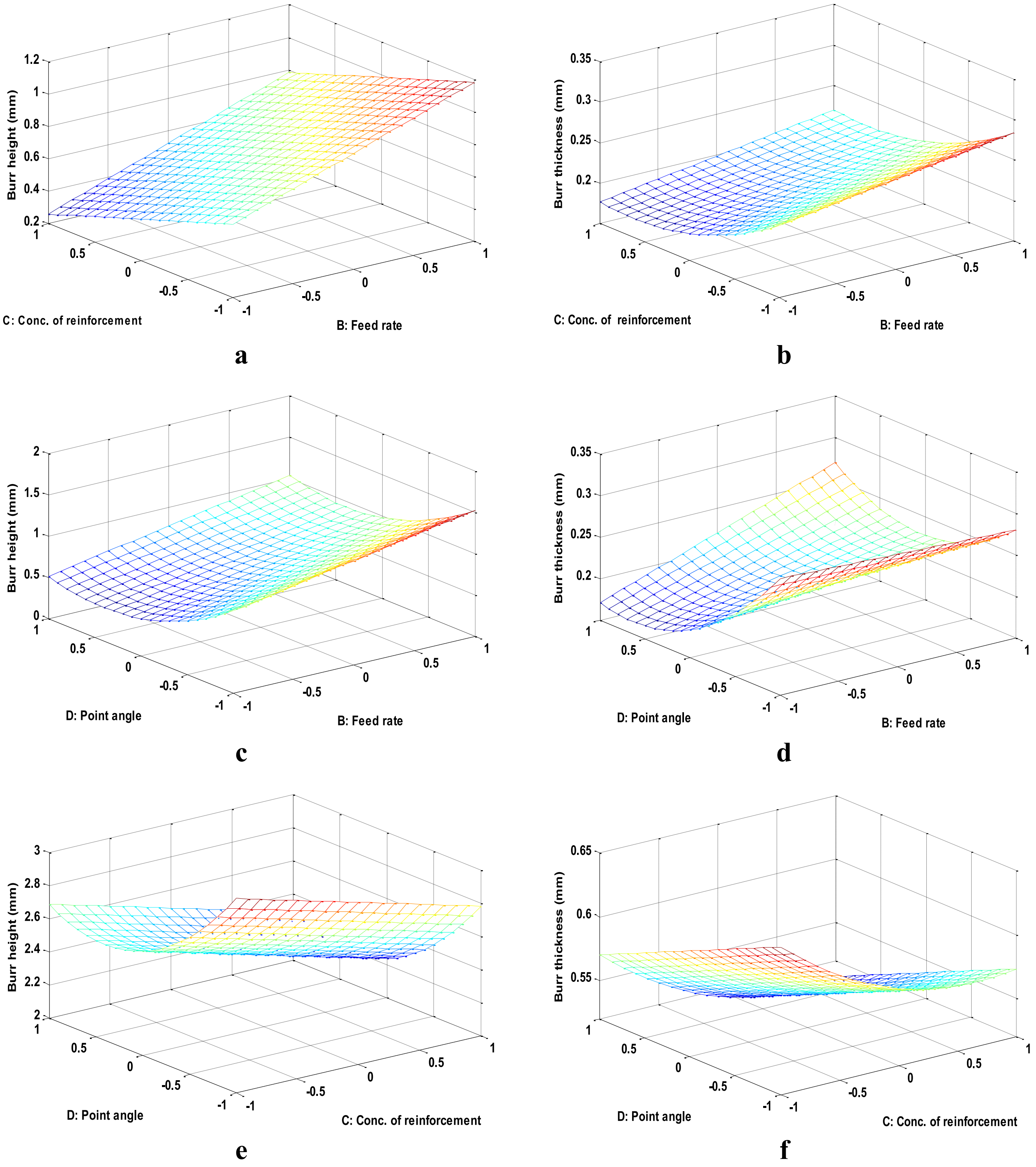

Fig. 4. Surface plots of burr height (a, c, e) and burr thickness (b, d, f).

to be increased approximately by 20–40% for the increase in cutting speed from 60 to 80 m/min.

Fig. 4 indicates the surface plots for the height and thickness of the burrs. Fig. 4a,b indicates the surface plots for height and thickness of the burrs produced respectively while drilling Al—SiC composites at 60 m/min cutting speed and for 118° point angle. Graphs indicate that the responses are minimum for lower feed and higher concentration of reinforcements. At lower feed rate, the matrix will not soften or yield and higher reinforcements in the matrix will provide higher debonding sites for the development of cracks along feed direction. Fig. 4c,d indicates the surface plots for height and thickness of the burrs produced respectively for Al—SiC composites with 15% concentration of reinforcement while drilling at 60 m/min cutting speed respectively. Both the responses are found to be minimum at lower feed and higher point angle. In the presence of tensile stresses exerted by higher point angle and in the absence of any significant yielding of matrix at low feed, the cracks will be developed and propagated from the sites where the reinforcement is pulled from matrix during drilling. Fig. 4e,f indicates the surface plots for height and thickness of the burrs produced

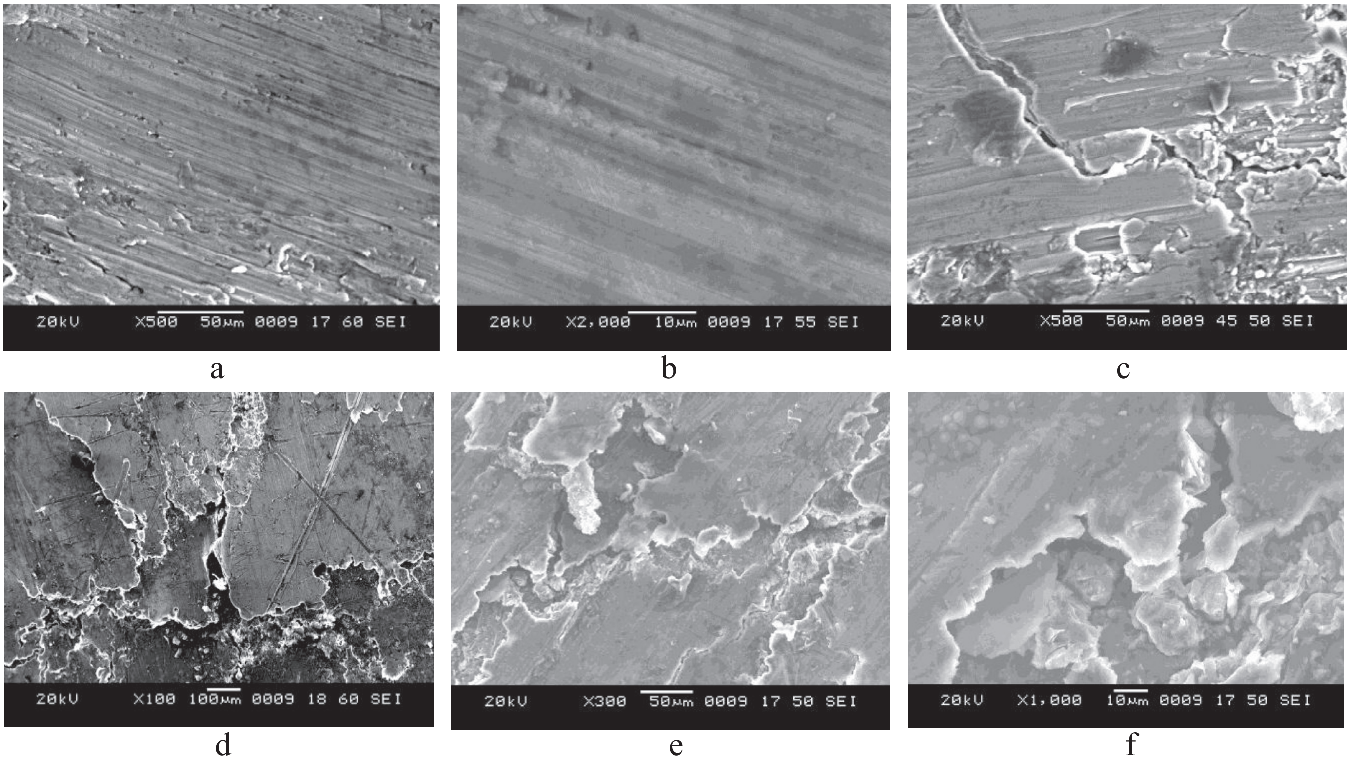

Fig. 5. Scanning electron micrographs of the burrs produced: (a, b) aluminum alloy drilled at 0.15 mm/rev feed rate, 60 m/min cutting speed, 140° point angle; (c) 15% concentration of SiC reinforcement drilled at 0.15 mm/rev feed rate, 60 m/min cutting speed, 140° point angle; (d) 15% concentration of SiC reinforcement drilled at 0.2 mm/rev feed rate, 80 m/min cutting speed, 140° point angle); (e, f) 30% concentration of SiC reinforcement drilled at 0.15 mm/rev feed rate, 60 m/min cutting speed, 118° point angle.

respectively for Al—SiC composites drilling at 60 m/min cutting speed and 0.15 mm/rev feed rate. Both the responses are minimum for higher point angle and higher concentration of reinforcements in matrix. Higher point angle exerts tensile stresses on the material and higher reinforcements provide availability of larger debonding sites for the crack development.

In the case of Al—SiC composites the initiation of micro-cracks at debonding site of reinforcement and the development of these cracks toward the feed direction are the main reasons for formation of irregular and smaller burrs at the exit. Hence in the absence of any reinforcements, surfaces of the burrs of aluminum alloy indicate no evidence of formation of any microcracks (Fig. 5a,b). Fig. 5c indicates the formation of thick micro-cracks along the entire surface of burrs and the plowing of reinforcements through the matrix before debonding at few locations. But at higher feed and cutting speed, matrix may yield. This can result in dislocation and formation of fewer microcracks at the surface (Fig. 5d). Fig. 5e,f indicates the surfaces of burrs produced for 30% concentration of SiC reinforcement. It indicates severe and thick microcracks leading to the exposure of SiC particles and the matrix delamination. Hence minimum burr height and thickness are achieved for higher concentration of reinforcement in Al—SiC composites.

Fig. 6 indicates the morphology of the chips produced in aluminum alloy and Al—SiC composites while drilling at cutting speed of 60m/min, feed rate of 0.1 mm/rev and point angle of 140°. Larger and highly curled chips with fewer cracks are formed in ductile aluminum alloy (Fig. 6a). In the presence of reinforcement in matrix the cracks are developed and propagated during the curling of chips. These cracks reach the edges of the chips, fracture and then result in smaller and discontinuous chips. Hence smaller chips are formed in 15% of SiC reinforcement (Fig. 6b). In case of 30% concentration of SiC reinforcement the chips indicate more cracks along the surface. Chips are found to be relatively smaller and flat as compared to chips found in previous materials (Fig. 6c).

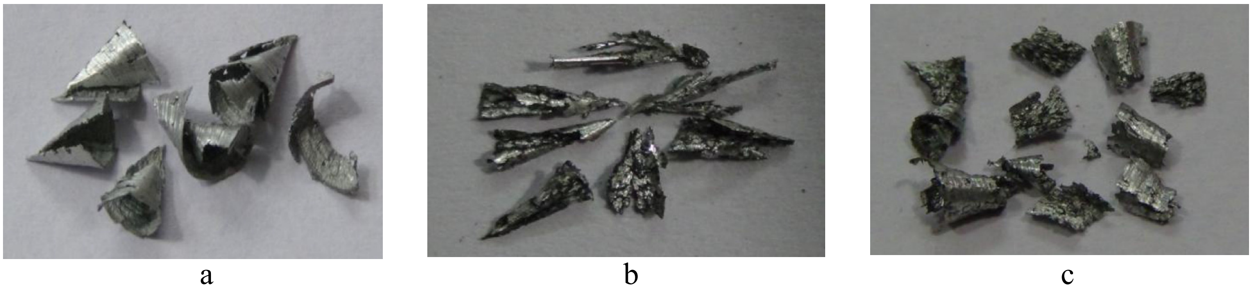

Fig. 6. Chips formed in drilling of (a) Al6061 alloy, (b) Al6061–15% SiC concentration and (c) Al6061–30% SiC concentration with cutting speed of 60 m/min, feed rate of 0.1 mm/rev and point angle of 140°.

4. Conclusions

In the present study, drilling of Al6061-SiC composites with different input process parameters were conducted for finding the factors that influences burr size. Response surface methodology was used for modeling of height and thickness of burrs. Based on the results, the following conclusions are derived.

1. Irregular burrs are formed while drilling these composites. The burr dimensions are found to be minimum for lower feed rate, higher point angle and higher concentration of reinforcements.
2. The results of ANOVA analysis revealed that feed rate plays a very important role for minimizing burr height followed by point angle. Similarly concentrations of SiC reinforcements in matrix and point angle of drill bit are the most significant factors for the burr thickness.
3. Scanning electron micrographs of the burrs are studied to understand the mechanism of burr minimization in Al—SiC composites. SEM images indicate matrix delamination, microcracks at the debonding sites and exposure of fibers along the burr surfaces.

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