

Optimization of machining parameters in drilling of LM6/B₄C/Fly ash hybrid composites

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Abstract. Metal matrix composites (MMCs), innovative replacements for traditional materials, are currently achieving a growing trend in engineering and research for operations like aviation, nuclear power, and automotive. Machining of MMCs makes it challenging to get good dimensional accuracy, surface finish and lower tool wear. Drilling is a necessary and immensely useful tool for component assembly in the manufacturing sector. As a result, optimization of drilling process variables is unavoidable. The fundamental purpose of this study is to use the stir casting technique to manufacture LM6/B₄C/Fly ash composites with 3, 6 and 9 wt.% of second phase materials. Taguchi's design of experiments strategy was used to drill with three levels of feed rate (F), spindle speed (S), drill material (D) and percentage of reinforcement (R) as input process parameters. Optimization of drilling variables for attaining lower surface roughness (SR) and burr height (BH) using single objective approach. The optimum process variable achieved for surface roughness is F1S3D3R2, i.e., 50 mm/min, 3000 rpm, TiN-coated drill bit and 6 wt.% of reinforcements (B₄C and Fly-ash) and for burr height is F1S3D3R3, i.e., 50 mm/min, 3000 rpm, TiN-coated drill bit and 9 wt.% of reinforcements.

Keywords: Drilling / hybrid composites / surface roughness / burr height / Taguchi

1 Introduction

The modern technology is progressing forward in a favourable way, owing to extraordinary improvements, discoveries, and advances in materials development. Many significant initiatives and researches have indeed been made for attaining better mechanical characteristics of materials [1]. Extensive investigations have been performed to meet the increased need for high-performance light-weight materials in the automobile, aircraft, nautical, shipyard, sporting equipment, healthcare devices, micro-structure, and spacecraft sectors. Investigators and materials scientists have been inspired to composites because of their enhanced mechanical and tribological properties [2]. Composites are made up of two or more macroscopic, microscopic, and nanoscale dimensioned particles with different physical and chemical components mixed together to provide the desirable features [3]. It is

widely known that two or more elements are joined to form composite materials, despite the fact that all elements have varied mechanical and chemical properties. When parent materials are joined, it creates an individual component that differs from the attributes of the parent materials. In composites, the load-bearing second phase material is typically the harder phase, whereas the soft phase is the matrix. The second phase material provides high strength, flexibility, and rigidity to any structural system, allowing it to withstand externally applied loads [4]. Furthermore, the reinforced particles enhance the product stiffness and strength, resulting in a massive structural load – bearing capacity. As per their composition, composites are divided into three divisions: MMC, PMC and CMC [5]. Due to its physical, mechanical, electrical and tribological features, metal matrix composites have recently piqued the interest of investigators and materials scientists. Furthermore, the automobile, automation, and aircraft industries are also seeking innovative lightweight materials to satisfy their needs. In Aluminium matrix composites, pure Al and Al- alloys serve as the continuous phase, while

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diverse metallic and non-metallic constituents such as Cu, SiC, Al_2O_3 , and SO_2 serve as second phase material [6]. It is observed that be emphasized that second phase materials are mixed with constituent materials of varying compositions to enhance mechanical properties in order to meet specifications. Because of their superior properties when compared to others, composites manufactured from Al alloys with varied second phase materials are extensively used in several advanced technical uses [7].

AMCs are extensively used in the manufacturing sector. Typically, ceramic materials are incorporated with aluminium based alloys to improve mechanical strength, wear and corrosion resistance [8]. Particulate-reinforced metal matrix composites (MMCs) are outstanding fabricators, low cost, and homogeneous materials with high stiffness but low strength [9]. It has attained a tremendous use tendency and significance due to its distinctive mechanical and physical characteristics. Such AMCs substituted majorly traditional ferrous materials in the automotive, marine, industrial robots and aircraft industries due to its features like highly resistant to wear, good strength & light weight [10,11]. AMCs reinforced with various elements such as Al_2O_3 , TiC, TiB_2 , TiO_2 , WC, Fe_3C , MoS_2 , SiC, B_4C , Gr and ZrB_2 are the promising materials in manufacturing applications [12]. Fly ash is a light weight, least expensive second phase material that is available in abundant. Fly ash reinforced composites are likely to break the financial barriers for a wide range of industrial applications. SR is a measurement of a work piece's surface quality that can be used to examine inhomogeneity caused by machining techniques [13]. The average roughness (R_a) is a frequently used industry criterion for assessing SR [14]. High SR in drilled holes has a direct influence on the synthesis method and, eventually, the production cost.

Furthermore, there is a probability of burr generation during drilling operation. Burrs are little deformed work piece fragments that form at the edges of holes at both the entry and exit. Burrs present at the entry are typically small and easier to extract; whereas, the burrs near the exit are harder to extract [15]. The work piece becomes permanently distorted as the drill reaches the hole's exit, and if the material cannot sustain the distortion, a fracture at the hole's edge is likely to develop [16]. Davim and MonteiroBaptista [17] performed drilling experiments and identified the mechanism of abrasive wear due to the presence of hard particulates in the continuous phase. Surface finish was considered to be influenced by the feed. While the ceramic particles enhance the mechanical characteristics of composite material but creates issues with machinability. Huang et al. [18] analyzed the influence of speed and feed rate on the drilling behaviour of SiC_p (56%)/Al composites materials. The feed factor was determined as one of the key cutting variables affecting the drilling efficiency.

Jayaganth et al. [19] performed drilling tests using different cutting speeds, feeds, cutting fluids as per Taguchi's L_9 array. Surface roughness values diminishes with raise in cutting speed and drop off in feed rate and machining time increases with raise in cutting speed and feed rate. To enhance the machinability of the SS410 optimum process parameters have been experimentally defined and verified. The coconut oil medium offered better machinability at higher speed and feed. Salura et al. [20] produced metal matrix composites with

different process parameter by hot press. The drilling experiments have been carried out without cutting fluid at the computer-controlled vertical machining centre. ANOVA was conducted to evaluate the impact of the output variables on the thrust force and surface roughness of composite materials. The influences of manufacturing variables such as temperature, pressure and reinforcement ratio have been analysed and their impacts have been depicted. The optimum level for each output factor is obtained by significantly increasing the Signal to Noise ratio strategy. The findings indicated that for both feed rate the second phase material ratio was the major variable influencing the surface roughness of the MMCs. A raise in thrust force and surface roughness values has been presented in the literature as the feed rate rose during machining. However, the thrust force and surface roughness values in this MMCs system continued to decline as the feed rate has increased, making this analysis more innovative.

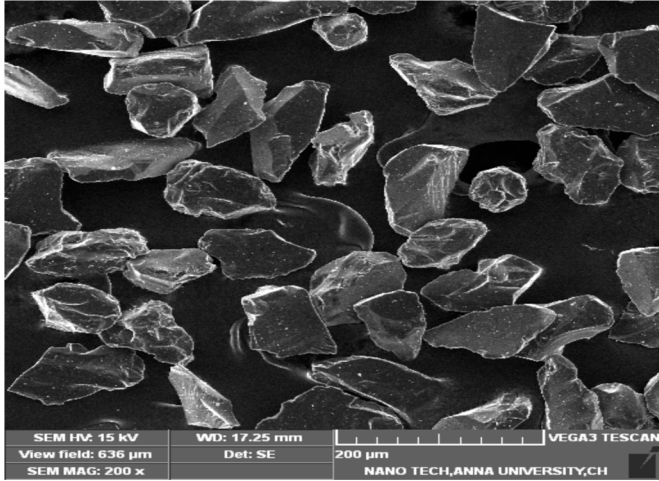
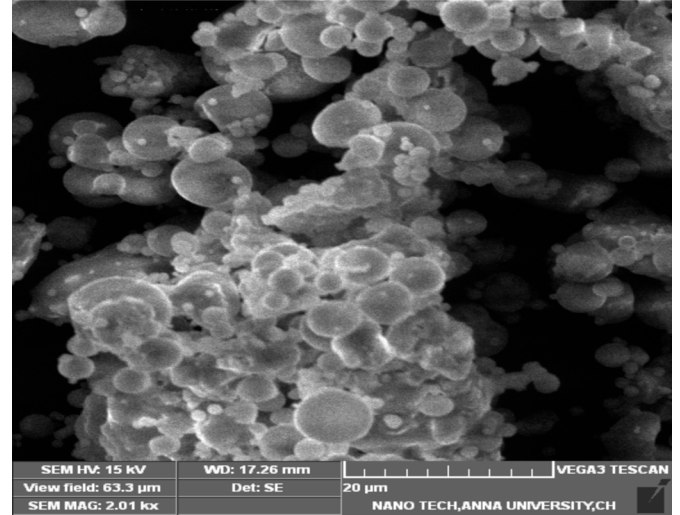
Ekici et al. [21] examined the impact of process variables on thrust force, surface roughness, dimensional accuracy and burr height properties while drilling Al/10B₄C and Al/10B₄C/5Gr composites with uncoated carbide twist drills under dry cutting conditions at 3 distinct speeds and feed rates. Using ANOVA, the percentage proportion of the process variables to the product quality was calculated, and statistical linear equations were constructed to estimate the quality properties. As a consequence of the experimental investigation, the 5% graphite second phase material of Al/10B₄C/5Gr reduced the thrust force and burr height during the drilling of the composites, enhanced the surface quality. Haq et al. [22] proposed a novel strategy for optimizing drilling variables for drilling Al/SiC MMC with multi-objective depending on the grey relational analysis orthogonal array. Ponnuel and Moorthy [23] analyzed the role of cutting parameters on multi-walled carbon nano tubes (MWCNTs) filled epoxy/glass fabric nano-composite hybrid polymer. Using grey relational analysis, optimal cutting samples were determined by simultaneously considering the surface delamination of the drilled holes at the entrance and exits.

Rajmohan and Palanikumar [24] explored the impact of thrust force in drilling hybrid MMCs with coated carbide drills. Composites used for this examination are 356-aluminum alloy reinforced with 25 micron SiC and 45 micron mica by stir casting. Using the main composite modeling method, tests are performed at a VMC. Using RSM, a model is built for correlating process variables with thrust force. The findings showed that the method designed for drilling of hybrid MMCs is suitable for estimating thrust forces. Daniel et al. [25] manufactured hybrid MMCs by adding SiC as the second phase material in various sizes at various levels (5%, 10% and 15%), whereas MoS_2 is fixed at 2% in aluminium matrix. Influence on process parameters of each control factor is evaluated using Taguchi S/N ratio approach. Furthermore, ANN model satisfies the most important method for predicting process parameters than the regression model. ANOVA suggest that the most important factor in response variable is the mass fraction of SiC, feed rate.

The impact of drilling operation factors on SR and BH of LM6/B₄C/Fly-ash hybrid composite material with three different drill materials such as HSS, carbide and TiN-coated carbide drills are presented in this research work. In the

Table 1. Elemental constituents of LM6 alloy.

Constituents	Si	Cu	Fe	Mg	Mn	Ti	Ni	Zn	Al
Wt.%	11.48	0.013	0.52	0.02	0.01	0.02	0.01	0.01	Remainder

**Fig. 1.** Surface morphology of B₄C.**Fig. 2.** Surface morphology of fly ash.

experiments, Taguchi's orthogonal array (OA) is being used. The validity of the model is checked using ANOVA. The findings show that the created model can accurately estimate the SR and BH in drilling LM6/B₄C/Fly-ash hybrid composites within the parameters observed. Researchers working on the drilling of other types of MMCs can get the optimum process parameters from this article. Even though the material is different, the trend is same. The effect of process parameters on various responses can be learnt from this study.

2 Materials and methods

2.1 Materials used

In this investigation, the continuous phase is LM6 alloy, and the second phase material is B₄C and Fly-ash. Materials were selected depending on their properties, affordability, and uses, among other factors. LM6 alloy is challenging to work, mainly for its capacity to draw, and then because of the tool's excessive quick wear induced by the higher amount of silicon. LM6 alloy has high corrosion resistance in standard atmospheric and marine conditions. In comparison to all other casting alloys, it may be cast into thin and complicated structures [26]. The elemental constituents of LM6 Al alloy were analysed and depicted in Table 1. The morphological structure of second phase material (B₄C and Fly-Ash) is shown in Figures 1 and 2.

2.2 Preparation of LM6/B₄C/fly ash hybrid composite material

An electrical furnace was used to heat LM6 alloy ingots to 850 °C using a graphite crucible. The molten aluminum was agitated to create a vortex, and then preheated (250 °C)

**Fig. 3.** Fabrication of LM6 alloy using stir casting setup.

second phase material such as B₄C and fly ash particulates were incorporated into the matrix. Then the mixture was agitated at 600 rpm for 10 min. Potassium hexafluorotitanate was being added to the mixture (K₂TiF₆, 1 wt.%). By weight percentage, the proportions of adding reinforcement (B₄C) were 1.5, 3, and 4.5%. In the same way, the fly-ash added % was 1.5% 3% and 4.5%. The melted material was transferred into the mold at 650 °C and allowed to cool to room temperature [27]. Figure 3 depicts the stir casting setup that was used in this research.

2.3 Drilling of aluminium matrix hybrid composites

Drilling trials were conducted on a Gaurav-BMV 35 T12 (Model) vertical machining centre (VMC) shown in Figure 4. The experimental data is obtained and recorded using a data gathering device operated by the computer. Main concern in drilling is the reliability of the drilled hole. The quality of the hole is primarily based on the TF generated during drilling and was obtained by Kistler dynamometer.

2.4 Design of experiments

Taguchi describes a product's quality; in terms of the loss the product imparts to society. Taguchi implies the use of signal-to-noise ratio (S/N) to evaluate the features of the quality. Taguchi method is the systematic implementation of experimental design and analysis for the goal of designing and enhancing the quality of products. Taguchi's strategy to variable design offers an effective and systematic method for design engineers to evaluate near-optimum performance parameters. The Taguchi approach uses DoE concept orthogonal arrays (OA) to test a huge number of factors with a limited series of experiments. Designing an experiment involves selecting the most appropriate orthogonal array (OA) and assigning the relevant columns to the variables and interactions of interest. There are typically different kinds of signal-to-noise ratios, for example, lower-the-better, higher-the-better, and nominal-the-best.

The primary aim of the experiment is to identify the variables that impact the drilling operation in order to produce the lowest TF. The studies were designed using an OA of L_{27} to correlate the influences of ' F ', ' S ', ' R ' and drill material (D). This study uses four variables with 3 levels each, requiring 81 trials for full factorial design but 27 experiments were used so all the combinations of the input parameters were not used. Optimizing input variables with 27 trials is more accurate in Taguchi's DoE and allows for the study of interaction between the variables, L_{27} OA was selected to carry out the research work. The orthogonal property is each parameter at three different levels were used equal number of times (9) in the 27 experiments. Process variables were selected based on relevant research as well as trial experiments [28]. From the series of experiments performed as well as based on the reported work on hybrid MMCs, four main drilling variables and their levels were chosen for the experiment. Table 2 describes the three level design selected for the drilling variables.

2.5 Drill-bit materials

HSS, carbide and TiN-coated are the three main types of drill bits used for drilling operation. The diameter, point angle and helix angle are equal for the used drills i.e., 6 mm, 118° and 30° respectively. Figure 5 depicts an image of the drills utilized in this study. Dry condition has been retained for experimental behavior. The images of drilled surface are shown in Figure 6.



Fig. 4. Vertical CNC machining centre.

3 Results and discussion

3.1 Microstructural analysis

Figure 7a shows the microstructures of LM6 aluminium alloy. The Al-Si eutectic particles are in spike and script like appearance, due to the higher percentage of silicon (Al-Si particles) in LM6 alloys. The acicular arm of the Al-Si is longer. Figure 7b shows the distribution of 3% hybrid (boron carbide and fly ash) in the aluminium matrix composites. The eutectic constituents of Al-Si of the alloy LM6 are long acicular, script like shape and unchanged. Figures 7c and 7d are the micrographs of hybrid metal matrix composite of LM6 alloy with 6% and 9% addition of hybrid (boron carbide and fly ash) composites respectively. The distribution of composites is even and Al-Si is finer. This characteristic homogenous distribution trend is maintained due to the presence of higher silicon content.

3.2 S/N Investigation of SR and BH (LM6/ B_4C /Fly Ash)

Table 3 shows the SR & BH values along with their S/N values.

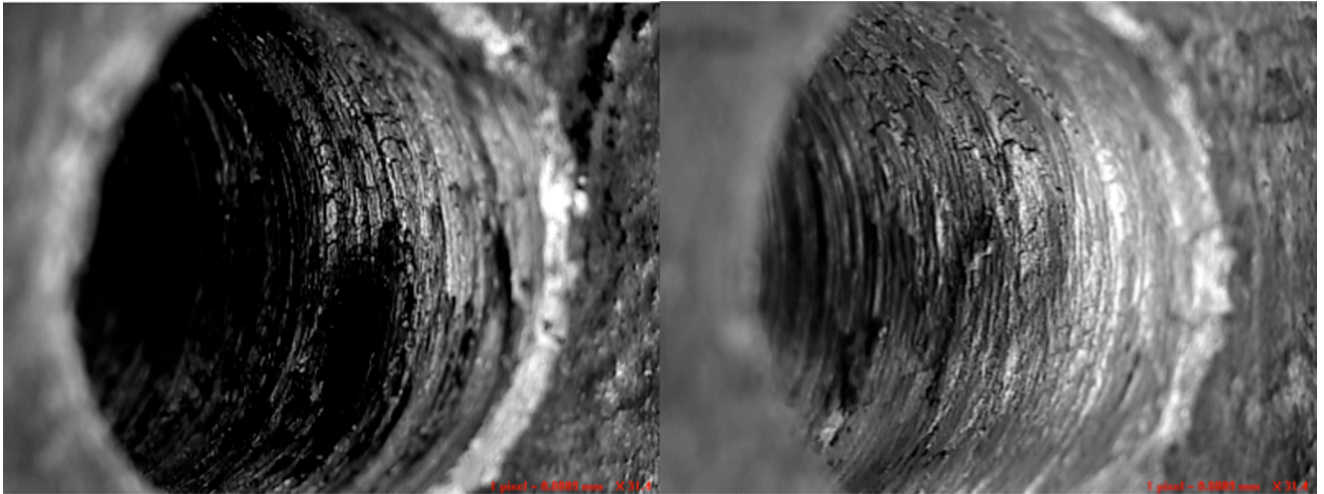
From Figure 8, SR is lowest at level 1 of ' F ' (F_1), level 3 of ' S ' (S_3), level 3 of drill material (D_3) and level 2 of reinforcement percentage (R_2). Hence, combination of $F_1S_3D_3R_2$ ($F_1 = 50$ mm/min, $S_3 = 3000$ rpm, $D_3 =$ TiN Coated drill, $R_2 = 6\%$) are optimal. From Table 4, feed rate is having more impact on SR followed by ' S ', ' D ' and ' R '.

Table 5 represents ANOVA for surface roughness and R^2 value is 98.18%, p -value is smaller than 0.05 for ' F ', ' S ' and ' D ' which shows that they have main impact on SR.

F -table value for the process variables is $F_{0.05, 2, 20} = 3.49$. From Table 5, F -test values for the ' F ', ' S ' and ' D ' are larger than F -table value, which shows that they are statistically significant. Feed rate (81.58%) has maximum contribution on SR and then spindle speed (14.07%) and

Table 2. Drilling variables and their levels.

Level	Feed rate (mm/min)	Spindle speed (rpm)	Drill material	Reinforcement (%)
1	50	1000	HSS	3
2	100	2000	Carbide	6
3	150	3000	TiN-Coated	9

**Fig. 5.** Photograph of drills.**Fig. 6.** Drilled holes images of AMC by VMS.

drill material (2.52%). Reinforcement percentage and interaction terms are very meagre, so they were pooled up with the error term.

3.3 Analysis and discussion of burr height (LM6/B₄C/FA)

From Figure 9, burr height is smallest at level 1 of '*F*' (F_1), level 3 of '*S*' (S_3), level 3 of '*D*' (D_3) and level 3 of '*R*' (R_3). Hence the combination of $A_1B_3C_3D_3$ ($A_1=50$ mm/min, $B_3=3000$ rpm, $C_3=\text{TiN coated drill}$, $D_3=9\%$) are

optimal. From Table 6, spindle speed is having more impact on burr height and then drill material, feed rate and reinforcement percentage.

Table 7 represents ANOVA for burr height and R^2 value for burr height is 92.23%, p -value is lower than 0.05 for '*F*', '*S*' and '*D*' which indicates that they have major influence on burr height whereas p -value is greater than 0.05 for reinforcement percentage and is insignificant.

F -table value for process variables is $F_{0.05, 2, 18} = 3.55$. From Table 7, F -test values for the '*F*', '*S*' and '*D*' are larger than F -table value, which indicates that they have

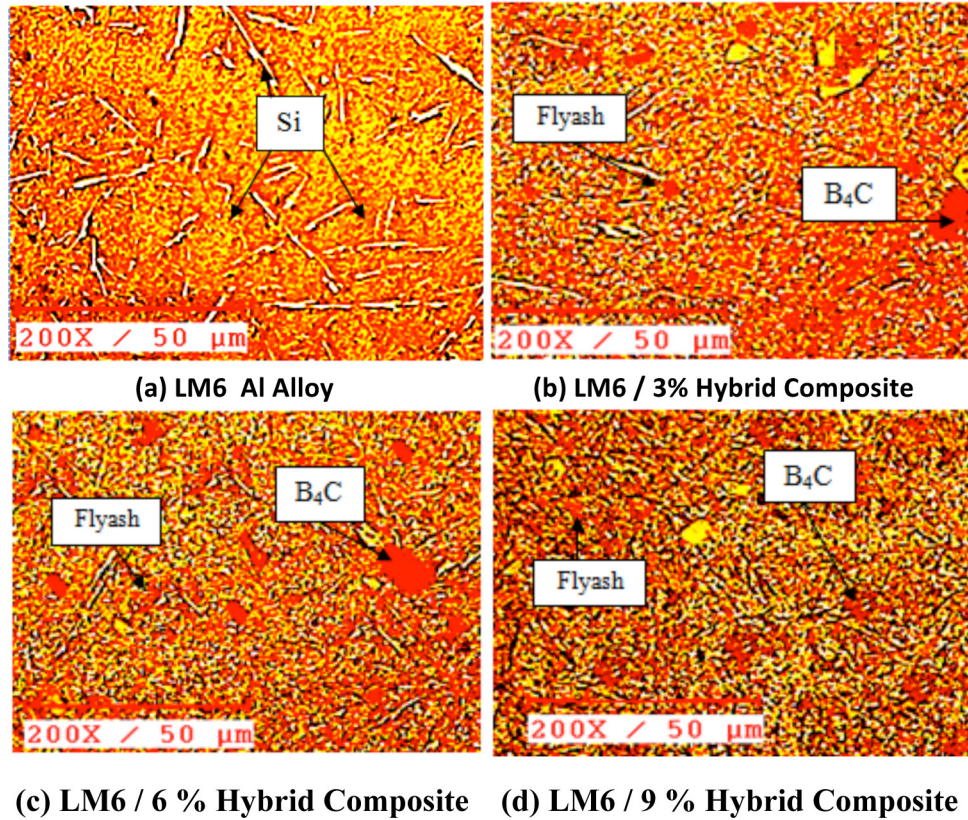


Fig. 7. (a–d) Micrographs of LM6/B₄C/Fly ash hybrid composites.

significant impact on burr height whereas F -test values for reinforcement percentage is lower than F -table value, which shows that it is insignificant. Spindle speed (73.41%) have more contribution on BH and then drill material (12.04%), feed rate (4.24%) and reinforcement percentage (2.54%). The contributions of interaction terms are very less, so they are pooled up with the error term.

3.4 Confirmation experiments

The outcomes of the investigations were examined to determine the best drilling conditions. The process variables such as ' F ' of 50 mm/min, ' S ' of 3000 rpm, TiN-coated carbide ' D ' and 6% ' R ' are the best qualities for attaining the lowest SR whereas ' F ' of 50 mm/min, ' S ' of 3000 rpm, TiN-Coated carbide ' D ' and 9% ' R ' are optimum for lowest BH. The experimental value for SR & BH is 1.96 μ m & 0.090 mm respectively, while the expected value for SR & BH are 1.90 μ m & 0.086 mm respectively. As a result, the optimization meets the requirements of the research.

3.5 Influence of drilling variables on SR and BH

Increase of feed rate from 50 mm/min to higher, SR also increases linearly. A lower ' F ' reduces the temperature which is created during drilling operation, which in turn, improves the surface quality. It is observed that lower feed

rate gives lower thrust force which implies that surface finish is good at smaller feed. The high TF, which increased the chip volume and thus influenced SR, was the reason for the high SR at high feed rate. The impact of ' F ' on SR is depicted in Figure 10a. As spindle speed increase, cutting time is reduced, which results in reduced thrust force, reduced work piece distortion and hence, surface finish is improved. SR is higher at lower Spindle Speed and then reduces (Fig. 10b). Figure 10c reveals that, SR of the hybrid composites were enhanced due to the TiN coating on the carbide drill bit. SR decreases initially with raise in the weight percentage of reinforcement. Further, increase in wt.% of the ' R ' raises the SR. which is due to the highest MMC hardness shown in Figure 10d [28].

As ' F ' increases, so does the TF and BH. For high feed rates, the BH is the largest [29]. Feed rate has more impact on BH and Low burr height is obtained at low feed [30]. It is observed from Figures 11a–11d, BH decreases with increase in speed of the spindle for LM6 alloy as well as LM6/B₄C, LM6/Fly Ash, LM6/B₄C/Fly Ash composite materials. Figure 11 shows that, carbide drill bit gives minimum BH for LM6 aluminium alloy, whereas TiN carbide drill bit provides less BH for composites and hybrid composite materials. Burr Height decreases with increase in reinforcement % for LM6/B₄C/FA composites. BH depends on ductility of the material and hence by increasing the reinforcement %, ductility is reduced.

Table 3. Experimental results of SR and BH with their S/N values.

Expt. No.	F (mm/min)	S (rpm)	D	R (wt.%)	SR (μm)	S/N of SR	BH (mm)	S/N of burr height
1	50	1000	HSS	3	2.65	-8.45	0.250	12.04
2	50	1000	Carbide	6	2.61	-8.32	0.202	13.89
3	50	1000	TiN coated	9	2.52	-8.03	0.131	17.65
4	50	2000	HSS	6	2.48	-7.89	0.125	18.06
5	50	2000	Carbide	9	2.47	-7.85	0.122	18.27
6	50	2000	TiN coated	3	2.45	-7.78	0.110	19.17
7	50	3000	HSS	9	2.41	-7.64	0.110	19.17
8	50	3000	Carbide	3	2.26	-7.08	0.101	19.91
9	50	3000	TiN coated	6	2.07	-6.32	0.095	20.45
10	100	1000	HSS	3	3.07	-9.74	0.226	12.92
11	100	1000	Carbide	6	3.04	-9.67	0.175	15.14
12	100	1000	TiN coated	9	3.00	-9.55	0.164	15.7
13	100	2000	HSS	6	2.88	-9.19	0.152	16.36
14	100	2000	Carbide	9	2.85	-9.11	0.134	17.46
15	100	2000	TiN coated	3	2.81	-8.97	0.122	18.27
16	100	3000	HSS	9	2.75	-8.79	0.119	18.49
17	100	3000	Carbide	3	2.65	-8.48	0.107	19.41
18	100	3000	TiN coated	6	2.55	-8.13	0.101	19.91
19	150	1000	HSS	3	4.21	-12.5	0.244	12.25
20	150	1000	Carbide	6	3.86	-11.7	0.214	13.39
21	150	1000	TiN coated	9	3.66	-11.3	0.199	14.02
22	150	2000	HSS	6	3.59	-11.1	0.152	16.36
23	150	2000	Carbide	9	3.52	-10.9	0.146	16.71
24	150	2000	TiN coated	3	3.38	-10.6	0.143	16.89
25	150	3000	HSS	9	3.34	-10.5	0.116	18.71
26	150	3000	Carbide	3	3.23	-10.2	0.140	17.08
27	150	3000	TiN coated	6	3.14	-9.94	0.083	21.62

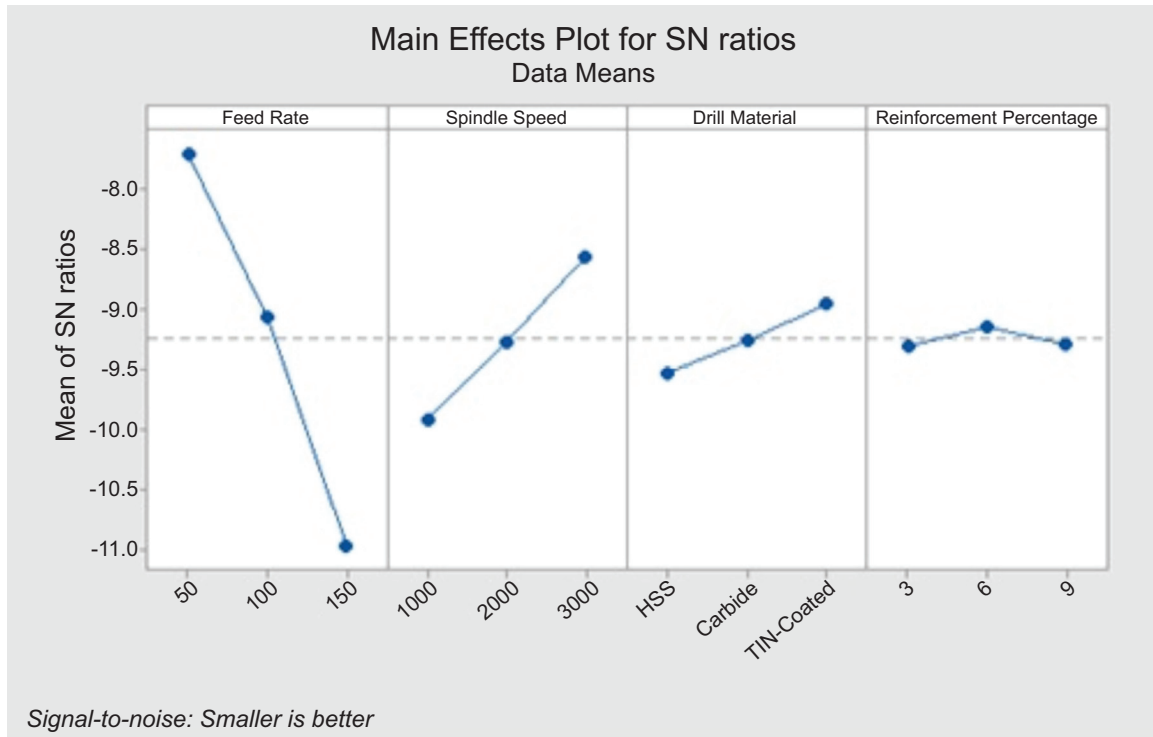


Fig. 8. Response graphs for surface roughness (LM6/B₄C/FA).

Table 4. Response table for SR (LM6/B₄C/FA).

Level	<i>F</i>	<i>S</i>	<i>D</i>	<i>R</i>
1	-7.708	-9.915	-9.527	-9.304
2	-9.068	-9.268	-9.261	-9.144
3	-10.964	-8.557	-8.952	-9.292
Delta	3.257	1.358	0.575	0.161
Rank	1	2	3	4

Table 5. ANOVA for SR (LM6/B₄C/Fly ash).

Source of variation	DoF	SS	MS	<i>F</i>	<i>P</i>	Contribution (%)
Feed Rate (A)	2	48.162	24.081	447.19	0	81.58
Spindle Speed (B)	2	8.306	4.1532	77.13	0	14.07
Drill Material (C)	2	1.489	0.7447	13.83	0	2.52
Pooled Error	20	1.077	0.0538			1.82
Total	26	59.035				100.00

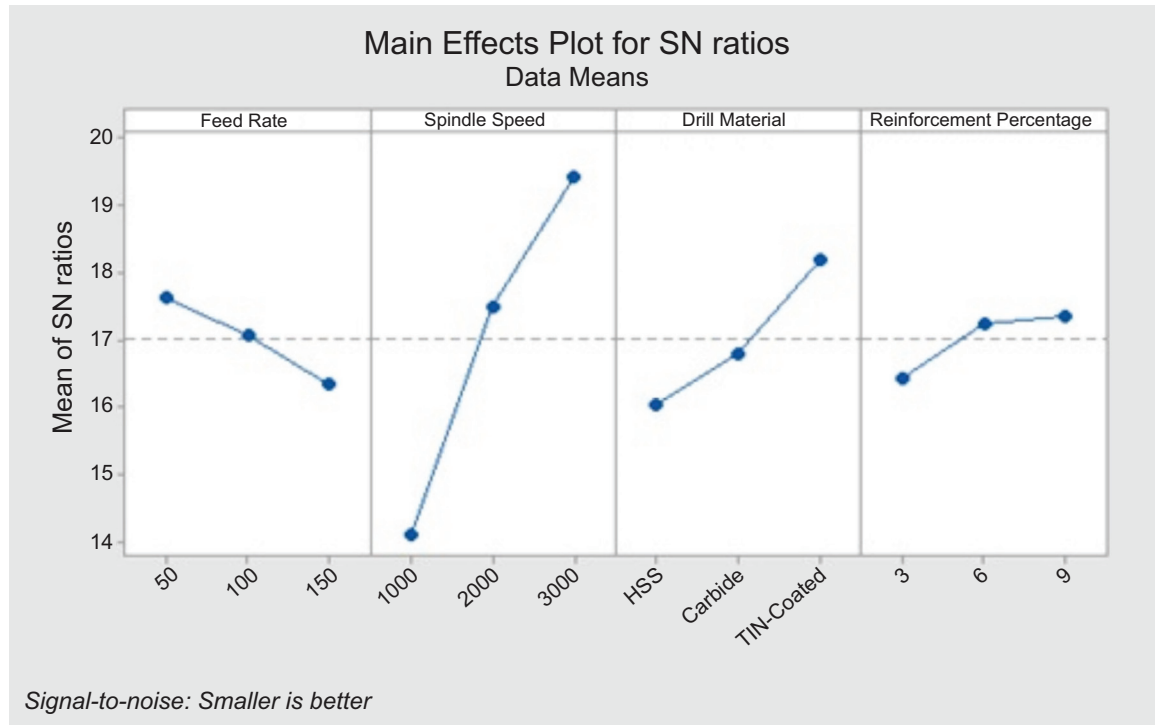


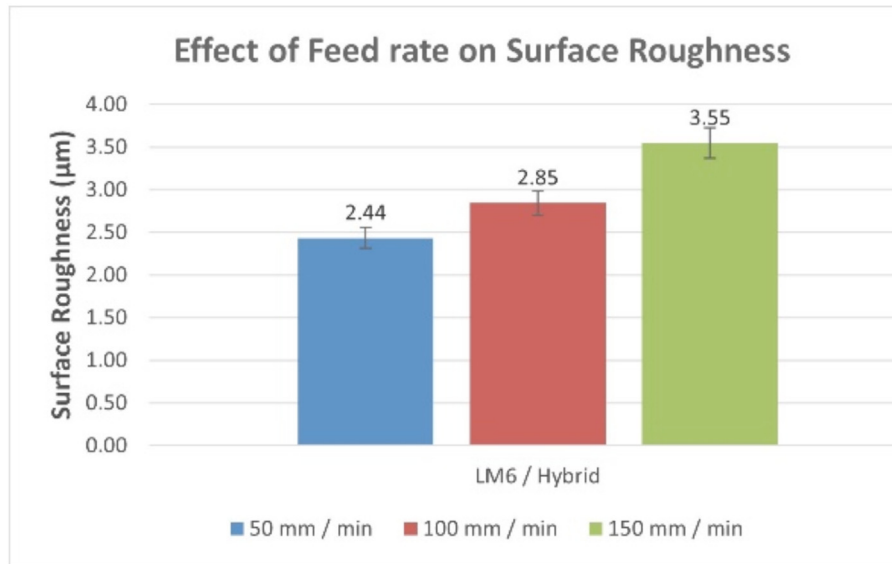
Fig. 9. Response graphs for burr height (LM6/B₄C/Fly ash).

Table 6. Response table for burr height (LM6/B₄C/Fly ash).

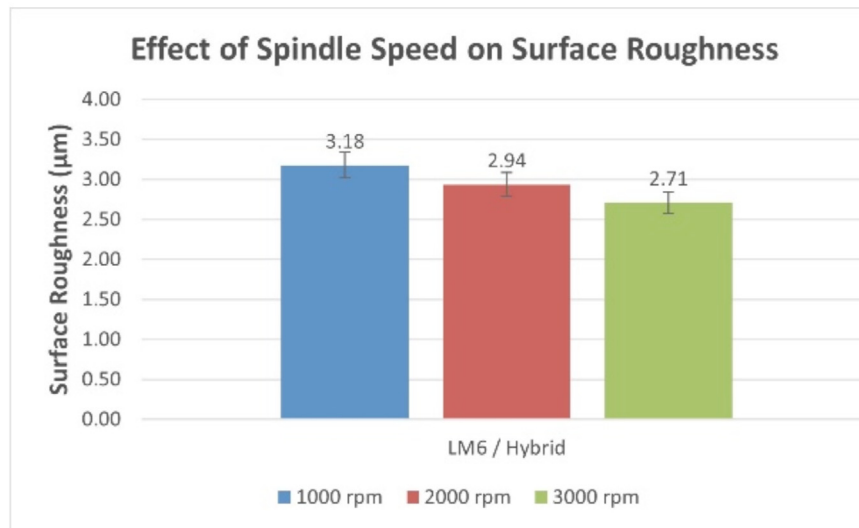
Level	<i>F</i>	<i>S</i>	<i>D</i>	<i>R</i>
1	17.63	14.11	16.04	16.44
2	17.07	17.51	16.81	17.24
3	16.34	19.42	18.19	17.36
Delta	1.29	5.3	2.15	0.92
Rank	3	1	2	4

Table 7. ANOVA for BH (LM6/B₄C/fly ash).

Source of variation	DoF	SS	MS	<i>F</i>	<i>P</i>	Contribution (%)
Feed rate (A)	2	7.506	3.7531	4.92	0.02	4.24
Spindle speed (B)	2	129.913	64.9563	85.09	0.00	73.41
Drill material (C)	2	21.313	10.6566	13.96	0.00	12.04
Reinforcement percentage (D)	2	4.494	2.247	2.94	0.08	2.54
Pooled error	18	13.742	0.7634			7.77
Total	26	176.968				100.00

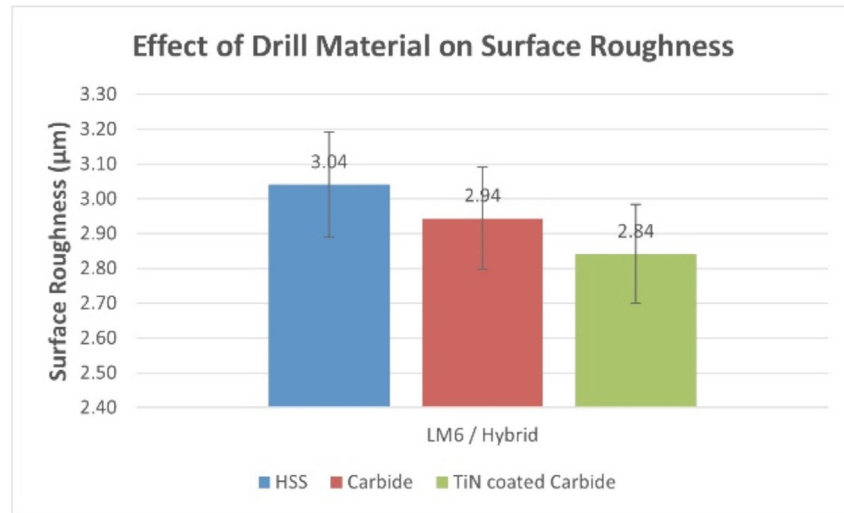


(a) Effect of Feed rate on SR

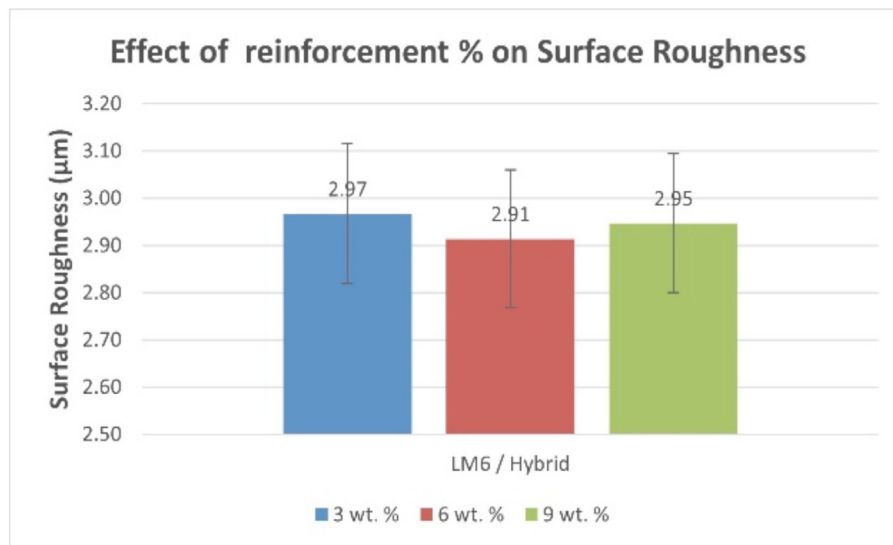


(b) Effect of Spindle speed on SR

Fig. 10. (a–d) Effect of process variables on SR.

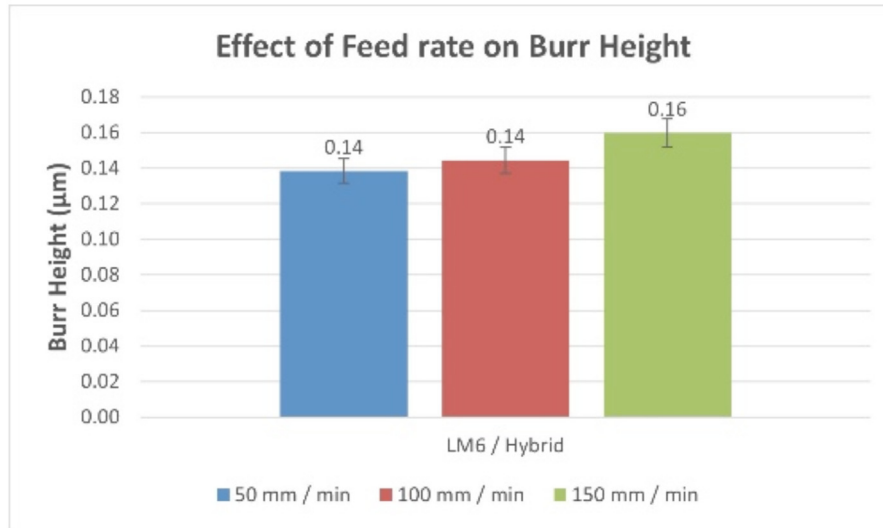


(c) Effect of Drill materials on SR

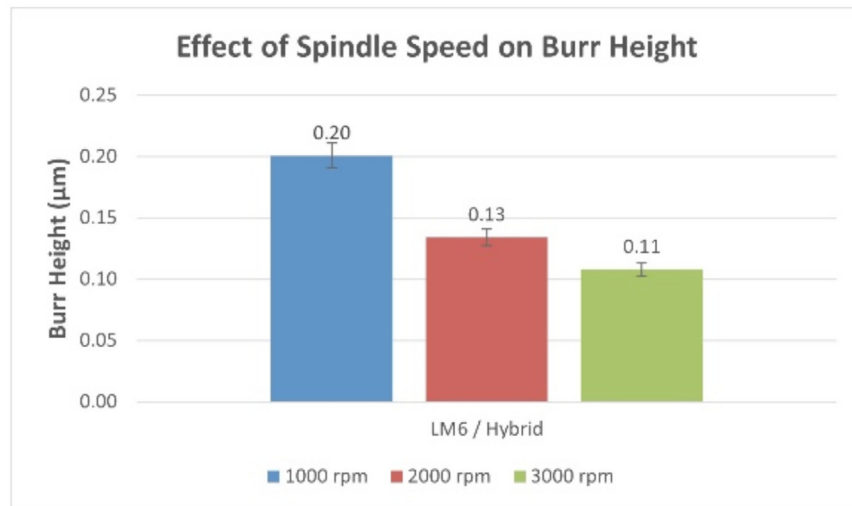


(d) Effect of Reinforcement % on SR

Fig. 10.(Continued).

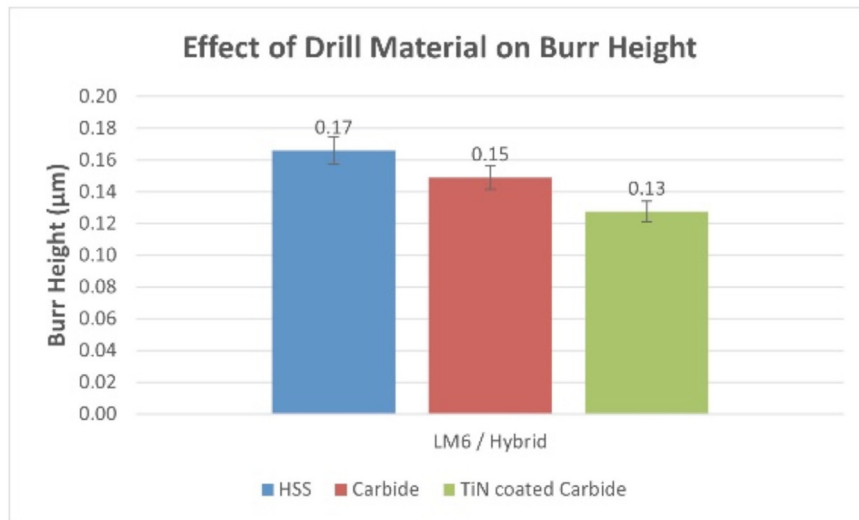


(a) Effect of Feed rate on BH

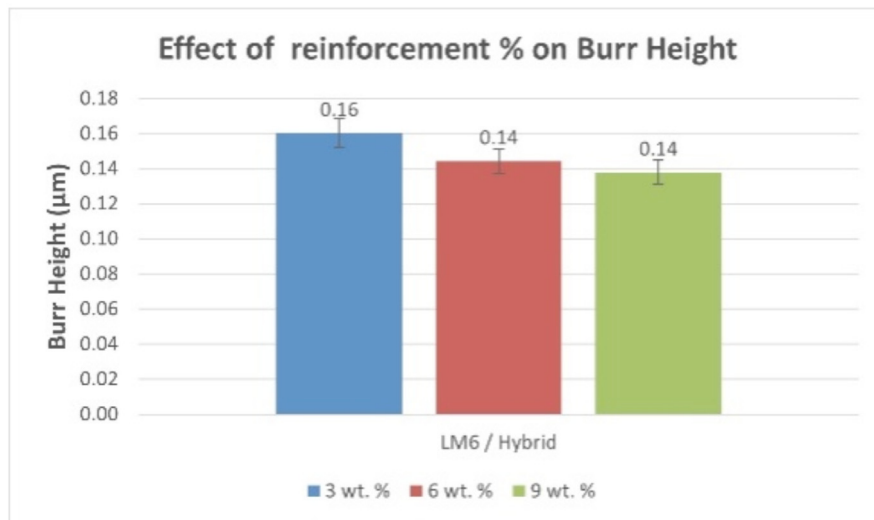


(b) Effect of spindle speed on BH

Fig. 11. (a–d) Effect of process variables on BH.



(c) Effect of Drill Material on BH



(d) Effect of Reinforcement % on BH

Fig. 11.(Continued).

3.6 Mathematical models of LM6/B₄C/Fly ash hybrid composites

Mathematical models of LM6/B₄C/Fly ash composites for surface roughness (SR) and burr height (BH) for HSS drill are presented in equations (1) and (2). Similarly, the equations developed for Carbide and TiN-Coated drill are presented in equations (3), (4) and (5), (6), respectively.

For HSS drill

$$\text{SR} = 2.420 + 0.011122 \text{ Feed rate} - 0.000234 \text{ Spindle Speed} - 0.0035 \text{ Reinforcement} \quad (1)$$

$$\text{BH} = 0.2598 + 0.000212 \text{ Feed rate} - 0.000046 \text{ Spindle Speed} - 0.00374 \text{ Reinforcement} \quad (2)$$

For Carbide drill

$$\text{SR} = 2.321 + 0.011122 \text{ Feed rate} - 0.000234 \text{ Spindle Speed} - 0.0035 \text{ Reinforcement} \quad (3)$$

$$\text{BH} = 0.2428 + 0.000212 \text{ Feed rate} - 0.000046 \text{ Spindle Speed} - 0.00374 \text{ Reinforcement} \quad (4)$$

For TiN-Coated Carbide drill

$$\text{SR} = 2.220 + 0.011122 \text{ Feed rate} - 0.000234 \text{ Spindle Speed} - 0.0035 \text{ Reinforcement} \quad (5)$$

$$\text{BH} = 0.2213 + 0.000212 \text{ Feed rate} - 0.000046 \text{ Spindle Speed} - 0.00374 \text{ Reinforcement} \quad (6)$$

4 Conclusions

The impact of drilling variables on hybrid composites led to the succeeding conclusions.

- LM6/B₄C/Fly-ash hybrid composites were fabricated using Stir Casting method.
- The most statistically significant factor on SR is the feed rate (81.58%) has maximum contribution on SR and then spindle speed (14.07%) and drill material (2.52%).
- The most statistically significant factor on BH is Spindle speed (73.41%) have more contribution on BH and then drill material (12.04%), feed rate (4.24%) and reinforcement percentage (2.54%).
- The process variables such as 'F' of 50 mm/min, 'S' of 3000 rpm, TiN-coated carbide 'D' and 6 % 'R' (F₁S₃D₃R₂) are the best qualities for attaining the lowest SR whereas 'F' of 50 mm/min, 'S' of 3000 rpm, TiN-Coated carbide 'D' and 9% 'R' (F₁S₃D₃R₃) are optimum for lowest BH.
- Confirmation studies reveal that the responses have a small margin of error.

The experimental results confirm that the proposed method in this study effectively improves drilling performance of composite materials.

Future work

In this research work the aluminium matrix composite plates were fabricated using stir casting technique, which can be fabricated using powder metallurgy route. Along with Boron Carbide and Fly ash, solid lubricants such as Graphite, MoS₂, Mica may be added in the composites for enhanced drilling results. The drilling studies performed in this research work can be carried out using different tool geometry, such as point angle, rake angle, helix angle, etc. The effects of the responses such as tool wear of the drill bits, circularity and cylindricity of the drilled holes can also be studied. The experimental results can be analyzed using other optimization techniques such as Grey Relational Analysis, Artificial Neural Network (ANN), Fuzzy Logic, Genetic Algorithm, etc. Fabricated composites can be used for performing other machining operations, such as wire EDM, milling, etc. Various destructive and nondestructive tests can be carried out for the characterization of the novel composites, such as tensile test, compression test, impact test, liquid penetrant test, magnetic particle inspection, eddy current test, ultra sonic test, radiography test, thermography test, etc.

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