Optimisation of drilling process parameters of aluminium matrix composites (LM5/ZrO_2)

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Abstract: Ceramics are incorporated into metal in the metal matrix composites (MMCs), which are tough to machine because of its abrasive quality. It is important to establish an effective technology for the efficacious machining of MMCs because of its future widespread use. The drilling of LM5/ZrO_2 composites employs Taguchi technique to find the optimum machining parameters to minimise surface roughness. The stir casting process is used to make a novel composite prepared by combining LM5 aluminium alloy with Zirconia with three distinct weight percentages (3, 6 and 9). In the produced composites, the effect of input parameters such as spindle speed, feed rate, drill material and reinforcement percentage on surface roughness was studied using L_{27} orthogonal array by conducting drilling operation in CNC machine. The research work was performed using the Taguchi's signal-to-noise ratio approach. Response graphs were used to evaluate parametric effects. Analysis of variance (ANOVA) was accompanied to find the related variables and assess their influence on the individualities of the response. Feed rate and Spindle speed are the most influential input parameters to achieve minimal surface roughness.

Keywords: drilling; composites; ANOVA; stir casting; Zirconia; Taguchi technique.

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1 Introduction

In this new era manufacturing materials have experienced a drastic transition. With traditional materials lagging behind to satisfy the demands of new technologies, many composites are gradually replacing materials to address this challenge. The aluminium matrix composites (AMCs) are processed using different manufacturing processes. Liquid metallurgy route is cheaper for large-scale production compared to powder metallurgy route (Ibrahim et al., 1991; Hashim et al., 1999). Owing to properties such as light weight, exceptional strength and outstanding corrosive resistance, more researchers are inspired by aluminium matrix composites (Nturanabo et al., 2019). Different machining methods (turning, drilling and milling, etc.) are introduced in the manufacturing industry to subtract the material from the work piece to produce the end product. Amongst the different processes of metal removal, drilling is the most essential aspect of metal removal relative to other conventional processes of machining. Various drilling techniques and methods of hole making are being utilised. The choice of various methods and tools depends on the size of the hole, type of work piece and the number of holes (Ravesh and Garg, 2012).

The manufacturing sectors concentrate on delivering high-quality goods at low cost, in time. Surface Roughness is measured as an indicator of product's technical efficiency (Prakash et al., 2018). Surface roughness has become one of the essential performance parameters that have a measurable impact on machined part's properties such as resistance to corrosion, fatigue behaviour and creep life, etc. (Garg and Goyal, 2015). It also influences various other mechanical properties of machined parts such as friction, scattering of light, flow of heat, lubrication and electrical conductivity, etc. The attainment of the optimal surface excellence is therefore of considerable significance for the mechanical parts' working behaviour (Prakash et al., 2018, 2015). During the work piece drilling, this have been understood that the requirements of drilling (drill point geometry, drilling parameters namely feed rate, spindle speed and work material) influence the process efficiency to a larger extent to extract the materials in direction of chips that travel all along the fluted shank of the depth of the drill. To maximise the economies of drilling activities these drilling conditions should be chosen. Using design of experiments (DOE) this can be accomplished (Rajmohan et al., 2012; Sarala Rubi and Prakash, 2020). The machining of MMCs is a significant area of study for decades. Previous research activities cover issues like tool-chip excess heat generation, study of cutting force chip formation, study of tool wear and tool-work interfaces, cutting force study, tool life, tool wear and machinability (Prakash et al., 2020; Sarala Rubi and Prakash, 2020). With even more focus on surface finish quality with a large production volume, research resources tend to have been redirected in the past few decades into researching surface roughness in metal machining (Sarala Rubi and Prakash, 2019a, 2019b).

However, it remains a difficult job for engineers due to the low machining properties of MMCs, several issues may be witnessed in MMC drilling, such as high thrust forces, excessive burr forming, poor surface finish and excessive tool wear. Taguchi technique is a useful tool for high-quality system implementation. This offers a clear, efficient and comprehensive approach to optimising the model for performance, consistency and expense. The methodology is useful if development criteria are qualitative and distinct. The evaluation of Taguchi parameters can improve effecting characteristics by establishing design parameters (Jebarose Juliyana and Prakash, 2020).

Cutting parameters like drill material, cutting speed and feed rate had a critical consequence on the roughness. The surface finish improves at lower feed rate, and higher cutting speed. With the volume of ceramic particles, the surface roughness values increased (Ficici, 2020). Feed rate and spindle speed are significant process parameters for managing surface roughness, wear of the tools, removal rate of materials and error in the diameter of the hole. It is also important to use the right combination of drill material, cutting speed and feed to minimise the variations that can influence the consistency of the drilled holes (Kumar and Packiaraj, 2012). However, according to Griffith's rule, the holes that have negligible surface roughness would have extended life cycles (Cavusoglu et al., 2018). The holes that are drilled with Carbide drill bit have greater surface finish than HSS and cobalt-coated HSS drill (Xavier et al., 2015). The important process parameters considered in drilling are spindle speed, the cutting tool and feed rate. The main influence and impact of process parameters on the responses were studied. Feed rate has the largest statistical effect on surface roughness accompanied by interaction between drill and feed (Navanth and Sharma, 2013). The analysis of the above study indicates that work was conducted to examine the impact of process parameters on surface roughness primarily also in drilling of several ferrous and non-ferrous alloys (Kurt et al., 2009). No research work has been carried out in optimisation of surface roughness in drilling of LM5/ZrO_2 composite earlier (Jebarose Juliyana and Prakash, 2020).

Henceforth in the present work the aluminium matrix composite (LM5/ZrO_2) is selected for the study. The effect of process parameters on surface roughness during drilling was analysed. The composite material is new and drilling process parameter optimisation studies of LM5/ZrO_2 composite material is the novelty of this work.

2 Materials and methods

2.1 Materials used

Materials were identified mainly due to property, applications and cost. The aluminium alloy LM5 has highest resistance to corrosion among all casting alloys. It also has excellent polished surface because of the enormous existence of aluminium. This highest consistency makes it ideal in ornamental and decorative uses, for marine pipe networks and food safety equipment. Very few research work are reported on AMCs reinforced with zirconia but no work has been carried out in LM5/ZrO_2 combination. So this combination is chosen for this present work. Optical emission spectrometry

(ASTM E 1251-07) reveals the LM5 aluminium alloy chemical composition is shown in Table 1.

Table 1 Chemical composition of aluminium alloy (LM5)

Constituents	*Zn*	*Ni*	*Pb*	*Mn*	*Mg*	*Fe*	*Cu*	*Si*	*Al*
Weight%	0.01	0.01	0.02	0.022	3.299	0.268	0.032	0.212	Remainder

Table 2 displays the chemical composition of Zirconium dioxide (ZrO_2). Zirconia is one of the ceramic materials which is widely studied. ZrO_2 is a crystalline white oxide of zirconium, also known as Zirconia. The exceptional strength but very minimal thermal conductivity is another excellent mix of properties of Zirconia.

Table 2 Chemical composition of ZrO_2

ZrO_2 (zirconium di oxide)	*Al_2O_3 (aluminium oxide)*	*HrO_2 (hafnium oxide)*	*Y_2O_3 (ytrium oxide)*	*Others*
92,642	0.253	1.78	5.3	0.025

2.2 Production of aluminium matrix composites

At the outset, aluminium alloy of grade LM5 was held in a graphite-coated crucible in the form of small ingots and liquefied in a furnace to 850°C. The graphite crucible is packed with a flux to regulate the oxidation of the molten material and the unwanted gases present in the mixture were removed by introducing argon gas.

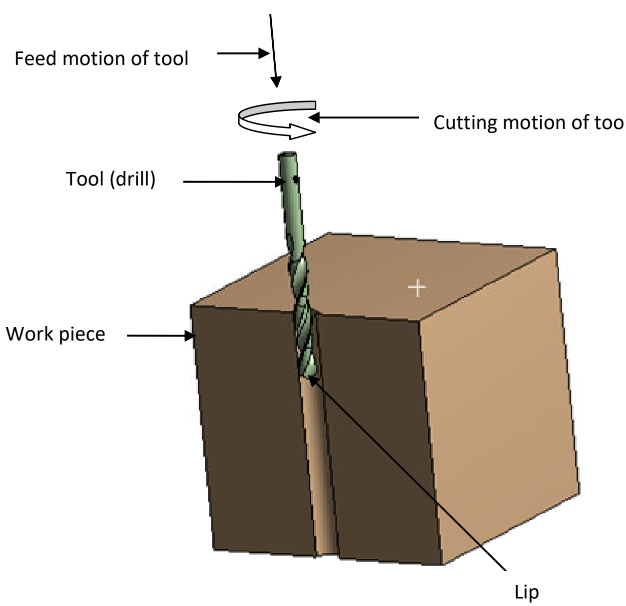
Figure 1 Stir casting setup with mechanical stirrer (see online version for colours)

In preheating furnace, the zirconia was preheated to 250°C for 20 minutes to eliminate the moisture. Zirconium di oxide of 60–80 μm size is applied to the molten metal. The mechanical stirrer was used to agitate the slurry. The maximum time for stirring was maintained for around 7 min at a speed of 600 rpm. Around the similar time, argon gas is blown into the molten mixture for 5 minutes to remove the gases completely contained in the melt. The pouring temperature was 750°C, and the mixture was transferred into a preheated (600°C) permanent die. Then the composites of LM5–ZrO_2 (3%, 6% and 9%) were fabricated by means of stir casting set-up (Figure 1). Composite plates were casted to the size of 120 × 120 × 23 mm and from that 120 mm length, 23 mm width and 10 mm thickness plate was cut and used for the present work.

2.3 Drilling of AMCs

Creation of holes in work pieces is a typical and most significant method in manufacturing industries. The holes are created using several methods and processes. The range of equipment and processes depends primarily on the depth of the hole, type of material, the number of holes created in the specified time. Drilling is a significant process of the various hole-making methods and is widely used. Drilling is the main step for any of the operations, for example tapping, reaming, and boring. When the drill revolves and feeds into the work piece, material is collected in the shapes of chips passing down the drill's fluted shank. Relative motion in between the work piece and the drill is required in drilling. For large work pieces the drill usually rotates and feeds into the work piece, and sometimes the work piece rotates and feeds into the drill. Figure 2 illustrates the method of drilling during which the drill is inserted into the work piece. The drill is forced against the work piece and rotated at revolutions of about hundreds to thousands per minute. The different drills used in this research work were shown in Figure 3. In the present work drilling operations were performed in model Gaurav-BMV 35 T12, vertical milling machine three axis (Figure 4).

Figure 2 Drilling process (see online version for colours)



The diameters of the holes made using drilling are generally slightly bigger than the diameter (oversize) of the drill. The extent of an over-size hinge on the drill selection, the model of machine used and the machine operator's expertise and experience.

Figure 3 Photograph of drill bits (see online version for colours)

Figure 4 Vertical machining centre (model Gaurav – BMV 35 T12) (see online version for colours)

2.4 Surface roughness

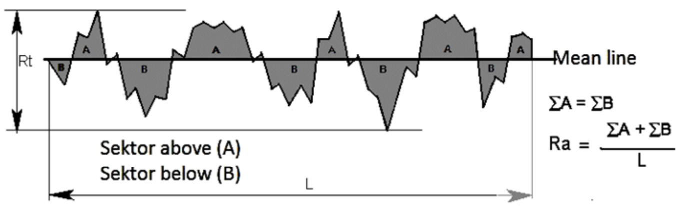
The product's technical efficiency is reflected as surface roughness. The achievement of the anticipated surface excellence is therefore of boundless significance for the well-designed behaviour of the mechanical parts (Rajesh et al., 2016; Balakrishnan et al., 2017). R_a and R_t (expressed in μm) are so often used in characterising the roughness of machined surfaces out of all the surface quality parameters. R_t is absolute roughness, and Ra is mathematical roughness [equation (1)].

$$R_a = \sum A + \sum B \tag{1}$$

The machined part Surface roughness was determined using a surface roughness tester (Surfcorder SE 3500) were shown in Figure 5.

Figure 5 Surface roughness tester (see online version for colours)

Figure 6 Schematic diagram of R_a and R_t



The mean line reveals that $\sum A = \sum B$ is displayed in Figure 6. Surface roughness is defined by numerous variables: parameters like cutting speed and feed rate, the tool material, forming of chips and the cutting forces, etc.

2.5 Design of experiments

The experiments were done on the basis of the L_{27} orthogonal array of the Taguchi and the main task of the study is to achieve minimal surface roughness. The process parameters and their levels used in the present study is shown in Table 3.

Table 3 Process parameters and their levels

Level	*Feed (mm/min)*	*Speed (rpm)*	*Drill bit material*	*Reinforcement%*
1	50	1,000	HSS	3
2	100	2,000	Carbide	6
3	150	3,000	TiN coated carbide	9

3 Results and discussion

The chosen OA was L_{27}, which consisted of 27 rows, leading to a total 27 experiments. The feed rate and spindle speed were assigned to the first and second columns respectively whereas the fifth and eighth columns were assigned to drill bit material and reinforcement percentage. Surface roughness was measured using a surface roughness tester (Surfcorder SE 3,500) and is tabulated in Table 4.

Table 4 Results of experiments

Exp. no.	*Feed*	*Speed*	*Drill material*	*Reinforcement percentage*	*Surface roughness (μm)*	*S/N ratio*
1	50	1,000	HSS	3	4.66	–13.37
2	50	1,000	Carbide	6	4.44	–12.95
3	50	1,000	TiN-coated	9	4.42	–12.91
4	50	2,000	HSS	6	4.31	–12.69
5	50	2,000	Carbide	9	3.25	–10.24
6	50	2,000	TiN-coated	3	3.25	–10.24
7	50	3,000	HSS	9	3.23	–10.18
8	50	3,000	Carbide	3	3.17	–10.02
9	50	3,000	TiN-coated	6	2.16	–6.69
10	100	1,000	HSS	3	5.76	–15.21
11	100	1,000	Carbide	6	5.49	–14.79
12	100	1,000	TiN-coated	9	5.34	–14.55
13	100	2,000	HSS	6	5.13	–14.20
14	100	2,000	Carbide	9	5.06	–14.08
15	100	2,000	TiN-coated	3	5.05	–14.07
16	100	3,000	HSS	9	4.44	–12.95
17	100	3,000	Carbide	3	3.83	–11.66
18	100	3,000	TiN-coated	6	3.5	–10.88
19	150	1,000	HSS	3	8.49	–18.58
20	150	1,000	Carbide	6	7.08	–17.00
21	150	1,000	TiN-coated	9	6.69	–16.51
22	150	2,000	HSS	6	6.64	–16.44
23	150	2,000	Carbide	9	6.57	–16.35
24	150	2,000	TiN-coated	3	6.31	–16.00
25	150	3,000	HSS	9	6.29	–15.97
26	150	3,000	Carbide	3	6.25	–15.92
27	150	3,000	TiN-coated	6	5.85	–15.34

3.1 Taguchi method – S/N ratios

The uncertainty is greatly reduced, and process parameters are optimised reliably by the Taguchi procedure. The signal to noise ratio (S/N) is used in this Taguchi method as an efficiency metric to assess process efficiency and metric deviations from optimum values. By calculating the signal to noise ratio (S/N ratio), the logarithmic metric, is defined. To decrease noise and the effects of unmanageable influences, larger S/N ratio values are required. Better output is shown by high S/N ratios. S/N ratios occur in three major groups, extremely lower-the-better, relatively higher-the-better, relatively nominal-the-best.

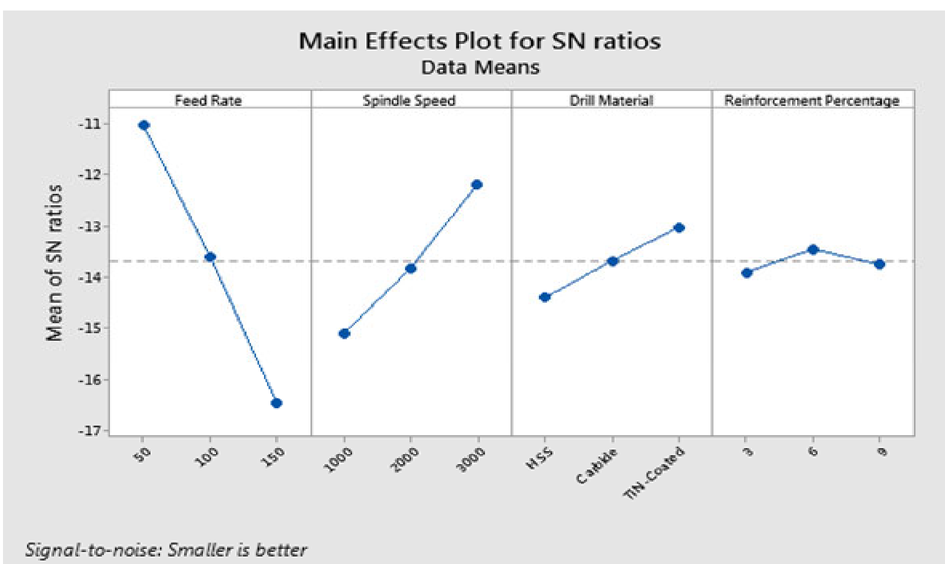
3.2 *S/N ratio – response table*

A response table for the S/N ratio (Table 5) is acquired using minitab software. The optimum parameter for surface roughness is to be found after measuring the S/N ratio for surface roughness. The delta computed value in the response table helps to assign a rank that could be subject to the response characteristics, from the maximum impact to the minimum effect. As the last delta value, the lowest value of the delta is taken and the highest delta value is ranked first. It can be concluded from Table 5 that the most significant process parameters for achieving minimal surface roughness are feed rate and spindle speed. TiN coated carbide tool on spindle's maximum speed and least feed rate reduces surface roughness on the work piece's material.

Table 5 Response table for S/N of surface roughness

Level	*Feed rate*	*Spindle speed*	*Drill material*	*Reinforcement percentage*
1	–11.03	–15.1	–14.4	–13.9
2	–13.6	–13.81	–13.67	–13.44
3	–16.46	–12.18	–13.02	–13.75
Delta	5.43	2.92	1.38	0.45
Rank	1	2	3	4

Figure 7 Response graphs for S/N of surface roughness (see online version for colours)



Target output characteristics for surface roughness are lower-the better. Table 5 displays that surface roughness decreases with the reduction of feed rate and increase in spindle speed. The feed rate, spindle speed and the type of drill are the most significant factors which affect the drilling process and the performance in the drilling process can be effectively improved by using this approach, the same trend is obtained by Rajmohan et al. (2012). In general, it is often inferred that the surface roughness reduces as the percentage of reinforcement grows to 6% and the hardness of the drill material is improved. TiN-coated carbide drills exhibits better performance than uncoated carbide drills for all the drilling operations about surface roughness properties. The surface roughness (R_a) values decreased with decreasing the feed rate and decreased with increasing the cutting speed (Ficici, 2020). The average output characteristics for all phases of the variable is shown in Table 5. The table provides a delta-based rating that relates to the relative magnitude impact. Rankings are awarded here based on delta values, the highest delta value is ranked 1, and the second highest rank 2, and so on.

The awarded ranks clearly state the overall significance of all variables. Delta values and ranks indicate that, the feed rate, Spindle speed, the drill material has the greatest impact. Figure 7 shows that the optimum criteria for achieving minimum surface roughness are feed level 1, drill material 3, speed level 3 and 6% reinforcement.

Table 6 ANOVA for S/N of surface roughness

Source	*DF*	*SS*	*MS*	*F*	*P*	*C%*
Feed rate	2	132.61	66.30	125.49	0.00	68.38
Spindle speed	2	38.44	19.22	36.37	0.00	19.82
Drill material	2	8.57	4.28	8.11	0.00	4.41
Feed rate*spindle speed	4	5.87	1.47	2.78	0.06	3.03
Pooled error	16	8.45	0.53			4.36
Total	26	193.94				100.00

To evaluate the significance of variables, ANOVA was performed. Therefore, Feed rate is the most significant factor in minimising surface roughness, spindle speed and drill material are also significant parameters for minimum surface roughness. The ANOVA results reveal that the feed rate was the most impactful factor on SR subsequently by rotational speed (Balaji et al., 2020). The study is on the drilling optimisation of the composite material, from the results it can be inferred that all the three composites have good machinability, regardless of the reinforcement percentage. After choosing the reinforcement percentage as one of the parameters, then only it was found that, it is the least significant parameter. In ANOVA Table 6, the reinforcement percentage was pooled up to the error term along with the insignificant parameters.

3.3 Confirmation experiment

The experimental results are scrutinised in order to find the optimal conditions. Input variables at level F_1 (50 mm / min feed rate), S_3 (3,000 rpm spindle speed), D_3 (TiN coated carbide drill bit) and 6% reinforcement are the optimal process variables from Figure 7 for accomplishing minimum surface roughness. The optimised parameters are the input parameters used by the Taguchi Technique to perform the confirmation experiment and also to minimise surface roughness. The predicted surface roughness is 2.45 μm and the experiment value is 2.16 μm. The optimisation approach consequently appears to hold well for this research.

4 Conclusions

Using the stir casting technique, the LM5/ZrO_2 Aluminium matrix composites have been successfully made. Based on the Taguchi DoE, drilling experiments were carried out. The signal/noise analysis allow obtaining minimal surface roughness by accompanying optimised parameters. The resulting conclusions from the analysis were disclosed.

1. The greatest statistical effect on surface roughness is traced by feed rate (68.38%) and is devoured by spindle speed (19.82%)
2. Studies of validation shows that very minimalism in error exists (<5%).
3. Optimisation verified the improvement in drilling efficiency of composites that use optimal parameters for machining.

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