Optimization of Process Parameters using Taguchi Technique for Drilling Aluminium Matrix Composites (LM6 / B₄C)

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Abstract. Due to their abrasive behaviour, metal matrix composites (MMCs) are difficult to machine, so it is necessary to develop a suitable technology for their efficient machining. The ultimate goal of the research is to study the impact of process variables such as reinforcement, drill type, speed and feed rate on the thrust force and burr height during AMC's drilling. Aluminium Matrix Composites were manufactured with LM6 aluminium alloy as matrix and B₄C as reinforcement through the low cost stir casting process. Experiments were performed using L₂⁷ orthogonal array in a CNC Vertical Machining Centre equipped with cutting tool dynamometer to measure the thrust force and burr-height was measured using vision measuring system. Experimental results demonstrated that this strategy enhances the performance characteristics expected in the drilling phase.

1. Introduction
A composite is a material composed of components manufactured by a physical mixture of pre-existing ingredients to obtain a new material with specific characteristics compared to the material's monolithic properties [1]. A composite is a material system that is closely bound to a few specific constituents. The reinforcement may be whiskers, particulates, plates, rods, etc. The matrix can be made of carbon, plastic, ceramic or organic material. A composite's constituents do not entirely dissolve or merge into each other, but act in concert. With enormous combinations, this yields infinite possibilities, making it an 'evergreen' field of study [2]. Aluminium composites have substantially improved properties, including high tensile strength, toughness, stiffness, low density and strong resistance to wear compared to alloys or other metals. There has been a huge interest in low-density and low-cost composites [3]. Aluminium bonded with silicon carbides are cheaper composite, offering greater strength and rigidity with negligible density improvement over the base alloy. Silicon Carbide are usually harder compared to the matrix of aluminium. The addition of SiC to the aluminium matrix makes machining more complex than traditional materials [4]. Ultra-hard abrasive reinforcement induces excessive wear of tools which causes major problem during the processing of such MMCs [5, 6]. Moreover, drilling MMCs is a complex task for industrial purpose because of the weak machining features of MMCs. Unlike traditional materials machining, several issues arise during MMC drilling, such as wear of equipment, heavy drilling forces, and burr. Around 75% of the components require some holes, so drilling is unavoidable [7, 8]. A bush is developed around the hole to strengthen it and the feature of the hole is equal to that of traditional drilling. It is also referred as flow drilling [9]. The reinforcement of carbides in the aluminium matrices leads to improve wear resistance and strength which makes them suitable for elevated temperature applications [10].
Design of Experiment (DOE) is a very good tool for modelling. DOE method using Taguchi method is made to optimize processes and to define the maximum combination of factors for a given approach [11, 12]. Taguchi designs offer a good method of designing products that perform in a variety of conditions continually and efficiently. Taguchi technique produces a typical orthogonal array that takes into account the impact of multiple factors on the target value and determines the experiment plan. Experiments are designed to examine the parameters impacting the response [13]. A standardized S / N ratio is used in this approach to calculate the current variation. Such Signal to Noise ratios are proposed to be used as representations of the cause on performance features of noise factors. Analysis of Variance is used to evaluate the response to the design parameters. It is a computational technique which quantitatively evaluates and represents as a percentage contribution to the overall response [14, 15].

2. Experimental Procedure

2.1. Materials Used
Aluminium alloy LM6 is a matrix material and boron carbide (B₄C) is the reinforcement in this analysis. Materials were carefully chosen depending upon characteristics, price, applications etc. Aluminium alloy (LM6) is difficult to process, first of all because of its ability to drag and secondly due to the extreme rapid wear of the tool caused by increased content of silicon. Under normal atmospheric and marine environments, aluminium alloy (LM6) reveals good corrosion resistance. It can be cast into thin and hard parts, compared to all other casting alloys. Table 1 reveals the chemical composition of aluminium alloy (LM6).

Table 1. Elemental Composition of Aluminium Alloy (LM6).

| Constituent | Silicon | Copper | Iron | Magnesium | Manganese | Titanium | Nickel | Zinc | Aluminium |
|-------------|---------|--------|------|-----------|-----------|----------|--------|------|-----------|
| Weight      | 11.48%  | 0.013% | 0.52%| 0.02%     | 0.01%     | 0.02%    | 0.01%  | 0.01%| Remainder |

Average size of 63 microns of Boron Carbide (B₄C) were used as one of the element for reinforcement. It has several properties, like high hardness and absorption of neutrons, which contribute in fabricating Boron Carbide widely used as soldier materials. For nuclear applications, boron carbide is unique. Figure 1 reveals the morphology of B₄C particles.

Figure 1. Morphology of Boron Carbide.
2.2. Fabrication of Aluminium Matrix Composites (LM6/B4C)

Stir casting technique has been used to produce aluminium matrix composites (LM6/B4C). Figure 2 demonstrates stir casting system with furnace. In a graphite crucible, the ingots of Aluminium Alloy LM6 are taken and heated in the electrical furnace. The Thermal energy is increased from lower temperature to 850°C. A solid dry hexachloro ethane (C2Cl6, 1 percent wt) degassed the melt at 800°C. Then, molten aluminium is agitated and the boron carbide particles preheated (250°C) are added. At 600 rpm, the slurry was stirred for 10 minutes. The melted metal is added to the potassium hexafluorotitanate (K2TiF6, 1% wt). The purpose of introducing titanium to Boron Carbide composite casting is to create an interface reaction layer containing TiC and TiB2 to develop bonding. Potassium and Fluoride contribute to eliminate the oxide film on the aluminium surface with the adding of Titanium (Ti) as K2TiF6. The boron carbide is added in the proportion of three, six and nine percentage. The dispersed stirred molten aluminium is transferred into cast iron moulds preheated at 650°C and lowered to ambient environment. The dimension of the composite plates are 100 x 100 x 10 mm.

![Stirrer and Furnace](image1)

**Figure 2.** Fabrication of Aluminium Alloy LM6 by Stir Casting Setup.

2.3. Drilling of AMCs

The drilling of aluminium metal matrix composites is an important manufacturing process. The experiments have been carried out with required cutting situations in the Vertical MachiningCenter. The data acquisition device controlled by the computer is used to obtain and store the experiment data. Kistler dynamometer is used to compute the thrust force.

![Vertical Machining Centre](image2)

**Figure 3.** Vertical Machining Centre (VMC 100).
2.4. Design of Experiments

Taguchi technique, a powerful tool for developing performance characteristics, has been used in this work. L-27 orthogonal array has been selected which has the capacity to control interactions between variables. Table 2 displays the levels of each parameter for drilling experiments.

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

2.5. Drilling Tool Materials

Three different cutting tool materials are used, which are HSS, Carbide and TiN coated carbide. The drill diameter is 6 mm, point angle is 118° and helix angle is 30° for all the three drills. The photograph of drills used in this research work is shown in figure 4.

![Photograph of Drills](image)

3. Results and discussions

The set chosen was the 27-row (L-27). The experimental strategy comprised of 27 runs using the first, second, fifth and eight columns for feed, speed, drilling material and reinforcement percentage respectively. Table 3 shows the experimental results.
Table 3. Experimental Results.

| Expt No. | Feed (mm/min) | Speed (rpm) | Drill Material | Reinforcement % | Thrust Force (N) | S/N Ratio | Burr height (µm) | S/N Ratio |
|----------|--------------|-------------|----------------|-----------------|-----------------|-----------|------------------|-----------|
| 1        | 50           | 1000        | HSS            | 3               | 144.4           | -43.191   | 0.113            | 18.938    |
| 2        | 50           | 1000        | Carbide        | 6               | 147.8           | -43.393   | 0.096            | 20.355    |
| 3        | 50           | 1000        | Coated         | 9               | 223.9           | -47.001   | 0.121            | 18.344    |
| 4        | 50           | 2000        | HSS            | 6               | 197.5           | -45.911   | 0.024            | 32.276    |
| 5        | 50           | 2000        | Carbide        | 9               | 233             | -47.347   | 0.228            | 12.854    |
| 6        | 50           | 2000        | Coated         | 3               | 78.27           | -37.872   | 0.226            | 12.905    |
| 7        | 50           | 3000        | HSS            | 9               | 145.5           | -43.257   | 0.131            | 17.655    |
| 8        | 50           | 3000        | Carbide        | 3               | 143.1           | -43.113   | 0.109            | 19.251    |
| 9        | 50           | 3000        | Coated         | 6               | 169             | -44.558   | 0.417            | 7.604     |
| 10       | 100          | 1000        | HSS            | 3               | 236.2           | -47.466   | 0.351            | 9.094     |
| 11       | 100          | 1000        | Carbide        | 6               | 225.4           | -47.059   | 0.288            | 10.802    |
| 12       | 100          | 1000        | Coated         | 9               | 304             | -49.657   | 0.036            | 28.955    |
| 13       | 100          | 2000        | HSS            | 6               | 249.9           | -47.955   | 0.068            | 23.307    |
| 14       | 100          | 2000        | Carbide        | 9               | 247.6           | -47.875   | 0.170            | 15.374    |
| 15       | 100          | 2000        | Coated         | 3               | 159.4           | -44.050   | 0.184            | 14.704    |
| 16       | 100          | 3000        | HSS            | 9               | 200.4           | -46.038   | 0.119            | 18.489    |
| 17       | 100          | 3000        | Carbide        | 3               | 215.9           | -46.685   | 0.176            | 15.073    |
| 18       | 100          | 3000        | Coated         | 6               | 224.7           | -47.032   | 0.077            | 22.233    |
| 19       | 150          | 1000        | HSS            | 3               | 318.3           | -50.057   | 0.390            | 8.179     |
| 20       | 150          | 1000        | Carbide        | 6               | 252.9           | -48.059   | 0.705            | 3.040     |
| 21       | 150          | 1000        | Coated         | 9               | 517.7           | -54.282   | 0.268            | 11.437    |
| 22       | 150          | 2000        | HSS            | 6               | 288.9           | -49.215   | 0.045            | 27.000    |
| 23       | 150          | 2000        | Carbide        | 9               | 250.8           | -47.987   | 0.209            | 13.583    |
| 24       | 150          | 2000        | Coated         | 3               | 228.7           | -47.185   | 0.564            | 4.969     |
| 25       | 150          | 3000        | HSS            | 9               | 242.4           | -47.691   | 0.577            | 4.776     |
| 26       | 150          | 3000        | Carbide        | 3               | 229.4           | -47.212   | 0.176            | 15.073    |
| 27       | 150          | 3000        | Coated         | 6               | 185.4           | -45.362   | 0.297            | 10.535    |

3.1. S/N Ratios - Taguchi Method

Taguchi method uses orthogonal arrays to minimize the uncertainty and to maximise the process characteristics. The S/N ratio is employed in Taguchi approach as a performance criterion for finding process reliability and calculating variance from optimal values. Larger values of S / N ratios are needed to decrease the noise and the influence of unmanageable variables. Higher the value of Signal to noise ratio, better is the quality. Figure 5 shows that the thrust force decreases with decrease in feed rate and increase in spindle speed. It is also inferred that the thrust force decreases with the decrease in reinforcement percentage of the material and increase in hardness of the drill material. The obtained results are in good agreement with earlier researches.
3.2. **Response Table for Thrust Force**

Table 4 shows the average response feature for each variable. Rank was allotted for highest variable to the least variable, probably based on the response characteristics, depending on delta value in the response table. More delta value is given first rank. From table 4, it can be concluded that feed rate and reinforcement percentage are the most influential process parameters for obtaining minimum thrust force. This is because of the phenomena that lower feed rate and less reinforcement percentage leads to less thrust force on the work piece material.

![Main Effects Plot for SN ratios Data Means](image)

**Figure 5.** Response Graphs for Thrust Force.

| Level | Feed  | Speed  | Drill  | Reinforcement |
|-------|-------|--------|--------|---------------|
| 1     | -43.96| -47.8  | -46.75 | -45.2         |
| 2     | -47.09| -46.16 | -46.53 | -46.51        |
| 3     | -48.56| -45.66 | -46.33 | -47.9         |
| Delta | 4.6   | 2.14   | 0.42   | 2.7           |
| Rank  | 1     | 3      | 4      | 2             |

3.3. **Analysis of Variance (ANOVA)**

Table 5 reveals the ANOVA for Thrust Force. Feed has contributed 42 % in determining thrust force, followed by speed, drill and reinforcement. The F-value from table at 5% significance level is $F_{0.05, 2, 6} = 5.14$. So, from ANOVA Table 5 we see that feed rate is the significant parameter for thrust force.
### Table 5. ANOVA Table for Thrust Force.

| Source           | DF | SS  | MS  | F    | P     | Contribution % |
|------------------|----|-----|-----|------|-------|----------------|
| Feed             | 2  | 99.376 | 49.688 | 6.08 | 0.036 | 42.698        |
| Speed            | 2  | 22.49 | 11.245 | 1.38 | 0.322 | 9.663         |
| Drill            | 2  | 0.797 | 0.398 | 0.05 | 0.953 | 0.342         |
| Reinforcement    | 2  | 32.831 | 16.415 | 2.01 | 0.215 | 14.106        |
| Feed*Speed       | 4  | 8.579 | 2.145 | 0.26 | 0.892 | 3.686         |
| Feed*Drill       | 4  | 5.669 | 1.417 | 0.17 | 0.944 | 2.436         |
| Feed*Reinforcement | 4  | 13.988 | 3.497 | 0.43 | 0.784 | 6.010         |
| Residual Error   | 6  | 49.012 | 8.169 |       |       | 21.059        |
| Total            | 26 | 232.741 |       |       |       | 100.000       |

3.4. S/N Ratios - Taguchi Method

Taguchi used orthogonal arrays to reduce uncertainty and the method features are maximized. The S/N ratio is used as a quality criterion in Taguchi approach to finding process accuracy and to determine variance from optimum values. Larger Signal to noise ratio values are required to reduce the noise and impact of uncontrollable parameters. Figure 6 shows that the burr height decreases with decrease in feed rate and increase in spindle speed. It is also inferred that the burr height decreases with the increase in reinforcement percentage of the material and decrease in hardness of the drill material.

![Main Effects Plot for SN ratios](image)

**Figure 6.** Response Graphs for Burr Height.

3.5. Response Table for Burr Height

The mean response feature for each variable is shown in Table 6. Rank has been assigned to the highest variable to the least variable, mainly based on the response features, depending on the response table delta value. First rank is given with more delta value. From table 4, it can be concluded...
that feed rate and reinforcement percentage are the most influential process parameters for obtaining minimum burr height. This is because of the phenomena that lower feed rate and less reinforcement percentage leads to less burr height on the work piece material.

Table 6. Response Table for Burr Height.

| Level | Feed Speed | Drill type | Reinforcement |
|-------|------------|------------|---------------|
| 1     | 17.8       | 14.35      | 17.75         | 13.13         |
| 2     | 17.56      | 17.44      | 13.93         | 17.46         |
| 3     | 10.95      | 14.52      | 14.63         | 15.72         |
| Delta | 6.84       | 3.09       | 3.81          | 4.33          |

3.6. Analysis of Variance (ANOVA)
Table 7 reveals the ANOVA for Burr height. Feed has contributed 19.5% in determining thrust force, followed by speed, drill and reinforcement. The F-value from table at 5% significance level is F0.05, 2, 6 = 5.14. So, from ANOVA Table 5 we see that no factor has significance on thrust force.

Table 7. ANOVA Table for Burr Height.

| Source            | DF | Seq SS  | Adj MS  | F   | P   | Contribution |
|-------------------|----|---------|---------|-----|-----|--------------|
| Feed              | 2  | 271.5   | 135.75  | 1.5 | 0.296 | 19.507       |
| Speed             | 2  | 54.36   | 27.18   | 0.3 | 0.751 | 3.906        |
| Drill type        | 2  | 74.15   | 37.08   | 0.41| 0.681 | 5.328        |
| Reinforcement     | 2  | 85.42   | 42.71   | 0.47| 0.645 | 6.137        |
| Feed*Speed        | 4  | 83.87   | 20.97   | 0.23| 0.911 | 6.026        |
| Feed*Drill type   | 4  | 208.15  | 52.04   | 0.57| 0.692 | 14.956       |
| Feed*Reinforcement| 4  | 71.25   | 17.81   | 0.2 | 0.931 | 5.119        |
| Residual Error    | 6  | 543.1   | 90.52   |     |      | 39.022       |
| Total             | 26 | 1391.79 | 100.000 |     |      | 100.000      |

3.7. Confirmation Experiments
Experimental results were analyzed to find out the optimum drilling conditions. Optimum features for getting minimum thrust force are feed rate of 50 mm/min, spindle speed of 3000 rpm, Titanium Nitride Coated drill material and 3% of reinforcement. The predicted thrust force is 138 N and the experimental thrust force is 143.1 N. So the optimization satisfies the research work. Optimum features for getting minimum burr height are feed rate of 50 mm/min, spindle speed of 2000 rpm, HSS drill material and 6% of reinforcement. The predicted value of burr height is 0.102 µm and the experimental burr height value is 0.024 µm. From the experimental results of burr height, we can see that only 6 values are less than the predicted value, so the optimization satisfies the research work.

4. Conclusions
The following conclusions were drawn by analyzing the impact of drilling process parameters of aluminum matrix composites.
i) Aluminium matrix composites (LM6/B4C) 3%, 6% and 9% were successfully produced through stir casting technique.
ii) Feed (42.698 %) has the highest statistical influence on Thrust Force followed by reinforcement (14.106%) and Speed (9.663%).

iii) Feed (19.507%) has the highest statistical influence on Burr Height followed by interaction between drill material and feed.

iv) Confirmation experiments show that there is a marginal error associated with the responses.

5. References

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