Optimization of cutting parameters of hybrid metal matrix composite AA6061/ ZrB$_2$ and ZrC during dry turning

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Abstract

The predominant aim of the research has been meant to evaluate cutting characteristic features of machining on AA6061/ZrB$_2$-ZrC hybrid composite metal matrix with polycrystalline diamond tool. Though researchers understand, Taguchi would be used for dry turning operations to find the optimal cutting parameters. We have used the Taguchi L16 orthogonal array in the current investigation to evaluate the cutting characteristics. Through this work it’s analyzed that the optimal cutting as well as main cutting parameters actually affects the cutting performance. In order to understand the effectiveness of investigational optimization, confirmatory tests have been carried out hybrid composites fabrication composite has proved that it has better machining characterization. Hence, the fabricated composite can be recommended for applications especially hypersonic flight and rocket propulsion systems and because of the presence of hard ceramic material it is used commercially for the manufacture of cutting tools inserts.

Key words: HMMCs, Microstructure, Machining, Optimization, Taguchi method.

1. Introduction

Over the decades Aluminum is considered as the best metal for industrial, aerospace applications, due to its enormous profitable properties Al is the most used material, years later many experimental investigations have taken place by incorporating various other metals & materials to strengthen its mechanical & physiochemical behaviours. hybrid metal matrix composites has proven the best performance and given sustainable results for industrial purposes [1]. In comparison with MMCs, HMMCs possess synergistic effects with the enhanced, supportive, attractive behavioural characteristics [2]. Due to its customised characteristics such as electrical conductivity, thermal conductivity, outstanding flexural strength, aluminium alloy 6061 has become a special material of choice. In the global marketplace, Aluminum reinforced HMMCs are growing extensively, making a significant contribution to the automotive, aircraft, aerospace and other sectors resulting from the material's natural properties [3-5]. Aluminium hybrid metal
matrix composites are engineered in an experimental finding through the process of stir cum squeeze casting. ZrO$_2$ particles were integrated to improve mechanical properties of aluminium. While graphite particles have improved thermal performance, this tends to increase the effectiveness of the component [6]. With a rapid increase in ZrO$_2$ weight percentages, hardness tends to increase as well. Results have shown that, comparison to conventional reinforced MMCs using the same micro / nano size reinforcements, HMMCs are significantly improved in their mechanical and physical properties. For MMC and HMMC, significant improvements in ductility and porosity were observed [7]. AA6061/6 wt. % SiC - 3 wt. %ZrO$_2$, in which hardness as a 95.5 BHN base material, hardness is enhanced by around 39 percentages. Compressive strength of 255.47 MPa, with a base alloy improvement of 20.4 percent. Enhanced by approximately 384.4 MPa of tensile strength. In comparison, 255.47 MPa compressive strength was found to have been increased by 24.2 percent of the base metal. Better bonding is shown by preheating the reinforcement particles. The mechanical and metallurgical reactions of composites were better. [8-9]. The HMMCs of Al$_2$O$_3$ / ZrO$_2$ / Gr has resulted in high porous space about 10.31%. AA2024 has become significantly enhanced the mechanical properties in the experimental investigations [10-11]. A study on MMHCs (Coconut coir Ash / SiC / Fly ash) resulted in significant improvements in mechanical properties including hardness. SEM has showed the homogenous particle distribution without any spaces in the matrix [12]. Values obtained a good agreement with the use of artificial neural networks. Squeeze Pressure: 140 MPa, 12 wt. % of B$_4$C, Die pre-heating temperature is 225°C. The statistical tool also revealed optimal process variables to obtain maximum mechanical properties [13-14]. ANOVA results which has indicated that superoxide dismutase contributes more with 81.74% followed by pressure with 8.94% and transverse speed with 5.22%. gray relational grade was high, that has increased about 0.0963. In machining time, reinforcement particles have been pulled because of high velocity which has resulted in micro voids, crater with Abrasive water jet machining process and also smooth surface has been formed at bottom due to depth of dispersion is decreased at SOD increases [15]. Reinforcement particles of complete matrix have improved the hardness of the sample, after incorporation of reinforcement’s mechanical properties has been rapidly increased. By increasing the weight percentages of reinforcement’s viscosity of the mixture become high [16]. The SCP value increased at low cutting velocity and higher feeding. This is due to a lower rate of workpiece strain, and other variables [17]. The reviewed literature clearly demonstrates both the application and the properties of MMCs and characterises research, strength, machining and optimization in the design and manufacture of hybrid metal matrix composites. Aluminium 6061 / ZrB$_2$-ZrC composites with very little work were compiled. The study suggests there is plenty of scope for this composite towards machining parameter optimization.

2. Fabrication Procedure of Hybrid Composite

In this research work, Aluminium AA6061 alloy was used as the matrix material. Aluminium rods were put inside a graphite crucible and kept inside an electric furnace under controlled atmosphere for fabrication of composite. The work samples of inorganic salts which includes
Potassium hexa-fluoro-zirconate, silicon carbide ceramic powder and Potassium tetra-fluoro-borate after preheating were added into molten aluminium melt at a temperature of 1250°C. The melt was continuously agitated for 45 minutes for a consistent distribution of in-situ synthesized particles. Melt was let into preheated mould of dimension diameter about 45 mm and length about 450mm was fabricated for the dry turning shown in Figure 1.

![Fabricated sample for turning and microstructural studies](image)

**Figure 1. Fabricated sample for turning and microstructural studies**

3. **Microstructure of AA6061 / 9wt% of ZrB\(_2\) and ZrC Composite**

Homogeneous reinforcement distribution has an internal influence on the mechanical characteristics as well as the adequacy of the composite material and it is very important to obtain the optimum thermal and also mechanical properties in MMCs. For the microstructural analysis of composites, square 10 mm side specimens have been prepared and then used. Generic metallographic methodologies and etching have been used for the preparation of specimens.

![SEM image for AA6061 containing 9% of ZrB\(_2\) and ZrC](image)

**Figure 2. SEM image for AA6061 containing 9% of ZrB\(_2\) and ZrC**
The surface morphology of ZrB₂ and ZrC synthesised in-situ, particles are considered as hexagonal and spherical shape that are located along its grain boundary restricting formation of intermetallic compounds shown in Figure 2. Thermal difference between insitu synthesised particles with good interface and the matrix moves the ZrB₂ and ZrC particles to their grain boundary during the solidification process.

4. Specification of the cutting conditions and their levels

The turning operation was carried through the Kirloskar Turn master-35 lathe with data acquisition system shown in figure 3-4. A Kistler multi-component type 9257B dynamometer as in figure 5 and a surface roughness tester named as Mitutoyo-SJ 210 shown in figure 6 were used during surface roughness and cutting force measurements. Poly-crystalline diamond tool has been used for machining of composite. Cutting speed, depth of cut and feed rate were the cutting parameters. There had been 3 stages of variation with in cutting parameters. As in the Table 1, the cutting speed ranged from 40, 60, 120, 160 m/min, the feed ranged from 0.12, 0.24, 0.36, 0.48 mm / rev and the cutting depth ranged from 0.2, 0.4, 0.6, and 0.8 mm. In the current investigation, the selected parameters for machining the composite are based on current projects discussed in the literature. Trial experiments were also conducted in order to maintain the feasibility of the levels / range of parameters reported by other researchers. The preceding cutting conditions were developed accordingly.

| Factors of the cutting parameters / Notation / Units | Level I | Level II | Level III | Level IV |
|-----------------------------------------------------|---------|----------|-----------|----------|
| Cutting Speed - CS / (m/min)                        | 40      | 80       | 120       | 160      |
| Depth of cut - DOC / (mm)                           | 0.2     | 0.4      | 0.6       | 0.8      |
| Feed Rate - FR / mm/rev                             | 0.12    | 0.24     | 0.36      | 0.48     |

Table 1. Levels of cutting parameters

Figure 3. Machining Setup

Figure 4. Data acquisition system
5. Experimental layout using L16 orthogonal array for dry turning

With the input variables mentioned in the table, 16 run experimental test was designed and those input variables were differed as shown below in Table 2.

Table 2. L16 Orthogonal array for machining parameters

| S. No | Cutting speed (m/min) | Depth of cut (mm) | Feed rate (mm/rev) | Cutting force (CF) | Signal-to-noise ratio for cutting force | Surface roughness (SR) | Signal-to-noise ratio for surface roughness |
|-------|----------------------|------------------|--------------------|--------------------|----------------------------------------|------------------------|---------------------------------------------|
| 1     | 40                   | 0.2              | 0.12               | 207.2              | -46.2235                               | 2.57                   | -8.43021                                   |
| 2     | 40                   | 0.4              | 0.24               | 266.2              | -48.4008                               | 2.49                   | -7.89347                                   |
| 3     | 40                   | 0.6              | 0.36               | 298.4              | -49.3988                               | 2.89                   | -9.19277                                   |
| 4     | 40                   | 0.8              | 0.48               | 353.4              | -50.957                                | 3.29                   | -10.3228                                   |
| 5     | 80                   | 0.2              | 0.24               | 215.2              | -46.5518                               | 2.21                   | -6.46759                                   |
| 6     | 80                   | 0.4              | 0.12               | 208.8              | -46.2588                               | 2.06                   | -6.21941                                   |
| 7     | 80                   | 0.6              | 0.48               | 326.6              | -50.2113                               | 3.03                   | -9.61443                                   |
| 8     | 80                   | 0.8              | 0.36               | 313.9              | -49.9256                               | 3.105                  | -9.6851                                    |
| 9     | 120                  | 0.2              | 0.36               | 215.9              | -46.6981                               | 1.995                  | -5.85521                                   |
| 10    | 120                  | 0.4              | 0.48               | 286.4              | -49.1295                               | 2.61                   | -8.2648                                    |
| 11    | 120                  | 0.6              | 0.12               | 231.6              | -47.2485                               | 2.41                   | -7.32136                                   |
| 12    | 120                  | 0.8              | 0.24               | 306.4              | -49.7186                               | 3.11                   | -9.50014                                   |
To evaluate difference between optimal values and quality parameters, S: N ratio had been used at every parametric level of the process [11]. The S: N ratio analysis reveals three different categories of quality characteristics, which includes lower, nominal, higher-the-better. In the current analysis, using the MSD equation, the lower-the-better was chosen.

$$\eta = -10\log \left( \text{MSD} \right) \quad \text{(Equ. 1)}$$

$$\text{MSD} = \frac{1}{n} \sum_{i=1}^{n} S_i^2 \quad \text{(Equ. 2)}$$

6. Results and Discussion

Table 3. Impact on cutting force and surface roughness of cutting parameters

| Parameters          | Cutting Force | Surface Roughness |
|---------------------|---------------|-------------------|
|                     | Source | D | F | Seq SS | Adj SS | Adj MS | F | P | Percentage (%) | Seq SS | Adj SS | Adj MS | F | P | Percentage (%) |
| Cutting Speed m/min | 3      | 54007 | 54007 | 18002 | 48.52 | 0.000 | 53.694% | 17.513 | 17.514 | 5.8395 | 0.000 | 42.833% |
| Depth of cut mm     | 3      | 16263 | 16263 | 5421  | 14.62 | 0.004 | 16.168% | 6.5080 | 6.5080 | 2.1693 | 0.001 | 15.911% |
| Feed Rate mm/rev    | 3      | 28084 | 28084 | 9361  | 25.23 | 0.001 | 27.921% | 16.3273 | 16.3273 | 5.4424 | 0.000 | 39.921% |
| Error               | 6      | 2227  | 2227  | 371   | 2.213%| 0.5457 | 0.5457 | 0.0909 | 1.334% |
| Total               | 15     | 100581|       |       | 100%  | 40.8993|     |       | 100%  |
Focusing on the parameters, dry turning was performed. From the analysis of the surface roughness graph, it’s been observed that roughness in surface is primarily affected by cutting speed in a rapid increase in mean S:N ratios observed along four levels of parameters [16]. In addition, surface roughness is least affected by depth of cut that is initiated by feed rate for all levels as shown in Figure 7 and 8. ANOVA was used to identify the percentage impact of individual cutting force and surface roughness parameters [17]. On the basis of ANOVA analysis, cutting speed was about 53.695 % and had a greater impact on cutting force, led by feed
and depth cut. The cutting speed with 42.83 % has showed was mostly influenced by surface roughness, which is followed by feed rate further followed by depth of cut as in Table 3. The notable cutting parameters for affecting the surface roughness and cutting force are cutting speed and feed. In addition, cutting depth, feed rate and cutting speed depending on S / N ratio and the ANOVA analysis are the optimum cutting parameters for surface roughness and cutting force. The important cutting parameters that affect the surface roughness and cutting force are cutting speed, feed rate and depth of cut.

7. Conclusion

- The composite with 9 wt.% of AA6061/ZrB$_2$-ZrC was produced by stir casting process.
- The homogeneous distribution of synthesised reinforcement particles in situ was revealed by the SEM images as well as noticed to have a bonding matrix and strong interface.
- The concentration of ZrB$_2$-ZrC particles synthesised in situ modified the grain structure of AA6061.
- The L16 run Taguchi investigation has been performed by employing Taguchi method specimens have been optimised.
- It has been observed from the ANOVA analysis and S:N ratio analysis that on increasing surface roughness and cutting force has a major impact on cutting speed.

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