Effect of Electrical discharge machining parameters on microwave heat treated Aluminium-Boron carbide-Graphite composites

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Abstract

Aluminium metal matrix composites have become the necessary materials in various engineering applications. Al 6061 is the matrix material in which boron carbide, one of the hardest material and graphite are reinforced and the composite was prepared by stir casting. Microwave post heat treatment of metal based components is a newer technique which is employed in this study. It provides unique microstructure and properties as a result of selective heating. In order to obtain solution heat treatment, the composites were heated up to 520°C and were maintained for a definite holding time at 520°C. Electrical discharge machining process was selected to machine MMC as it is difficult to machine by conventional machining. EDM machinability studies were carried out on the heat treated Al-B4C (15 vol%) graphite (5 vol%) and compared with EDM machined with conventionally heat treated composites. EDM process parameters optimization was carried out using Taguchi design with input parameter such as pulse on time, pulse off time and current density for the material removal rate (MRR) and tool wear rate (TWR) as response parameters. Microwave heat treated composite exhibited higher hardness than the conventionally heat treated composites. Pulse off time and pulse on time was a non-linear function for the material removal rate of the composite and the most influential parameters for the MRR were determined.
1. Introduction

Aluminium metal matrix composites are widely used in various engineering fields such as aerospace, marine and automobile products such as engine piston, cylinder liner, brake disc/drum etc [1]. Aluminium alloy 6061 is typically characterized by properties such as fluidity, castability, corrosion resistance and high strength-weight ratio is the matrix material [2]. Al 6061- B₄C dispersed with solid lubricant particles such as graphite has been established as potential engineering materials of a number of antifriction applications. Heat treatment is carried out for modifying the characteristics of metals and alloys to make them more suitable for a particular kind of application. It can greatly influence physical and mechanical properties such as strength, hardness, ductility, toughness and wear resistance of the alloys without changing the product shape [3]. Conventionally processed or cast products exhibit higher porosity and coarser microstructure which affect the physical and mechanical properties of products. Microwave heating overcomes the negative effects of conventional processing. Microwave post heat treatment of components is a newer technique employed in this study. In microwave heating, heat is generated internally within the material and the sample becomes the source of heat [4]. Microwave heating process improves the product uniformity by way of providing unique microstructure and properties as a result of selective heating. Boron carbide, one of the hardest materials is reinforced in Al matrix. It is therefore difficult to machine the composite by conventional machining process. Unconventional machining process is a suitable process for machining Al (6061)-B₄C-graphite composite. Hence electrical discharge machining process is selected to machine MMC.

Nomenclature

| Nomenclature | Description |
|--------------|-------------|
| MRR          | Metal removal rate |
| TWR          | Tool wear rate |
| Al-B₄C-graphite | Aluminium Boron Carbide Graphite composite |
| MMC          | Metal matrix composite |

2. Experimental details

2.1. Material details

Aluminium 6061 alloy is the matrix material. Magnesium and silicon are major alloying elements in Al 6061 and it exhibits good mechanical properties and good weldability. The chemical compositions and properties of Aluminium 6061 alloy are shown in Table 1 and Table 2 respectively.

Table 1 Chemical Composition of Al6061 by Weight percentage [5]

| Material | Weight(%) |
|----------|-----------|
| Si       | 0.62      |
| Fe       | 0.33      |
| Cu       | 0.28      |
| Mn       | 0.06      |
| Mg       | 0.9       |
| Cr       | 0.17      |
| Zn       | 0.02      |
| Ti       | 0.02      |
| Al       | Remaining |

Table 2 Properties of Al 6061 alloy

| Property                      | Al 6061 alloy |
|-------------------------------|---------------|
| Hardness                      | 60 HRB        |
| Density                       | 2.7 g/cc      |
| Elongation                    | 12%           |
| Modulus of Elasticity         | 69 GPa        |
| Ultimate Tensile Strength     | 310MPa        |
| Yield strength                | 276 MPa       |
Graphite and boron carbide are used as reinforcements. Graphite, an allotrope of carbon has a layered, planar structure with carbon atoms arranged in a honeycomb lattice in each layer with separation of 0.142 nm, and inter planar distance is 0.335 nm. The properties of commercial graphite are shown in Table 3. Boron Carbide is the third hardest material after diamond and cubic boron nitride. As a result of its high hardness, Boron carbide can be sintered only using sintering aids. It also exhibits good chemical resistance and low density. The properties of boron carbide are listed in Table 4.

| Property                      | Commercial Graphite [6] |
|-------------------------------|-------------------------|
| Porosity (%)                  | 0.7-53                  |
| Modulus of Elasticity (GPa)   | 8-15                    |
| Compressive Strength (MPa)    | 20-200                  |
| Thermal Conductivity (W/mK)   | 25-470                  |
| Flexural Strength (MPa)       | 6.9-100                 |
| Specific Heat Capacity (J/KgK)| 710-830                 |

| Property                  | Units       |
|---------------------------|-------------|
| Density (g/cm³)           | 2.52        |
| Young’s Modulus (GPa)     | 450         |
| Melting point (°C)        | 2445        |

2.2 Fabrication of Composites

The Al-B₄C-graphite composites were fabricated using stir casting method, a liquid state method of composite materials fabrication, by introducing small pieces of Al 6061 from ingots into the crucible. The percentage of graphite and boron carbide added to melt in the volume percentage of 5 and 15. This method is most economical to fabricate composites with discontinuous particulates. In this process, the matrix alloy (Al-6061) was first superheated above its melting point and then the temperature was lowered gradually below the liquidus temperature to maintain the semisolid state of the matrix alloy. At this stage, the graphite and boron carbide particles were introduced into the slurry and mixed. After mixing, the composite slurry temperature was increased so as to obtain fully liquid state and stirring was continued to about five minutes at an average speed of 300-350 rpm. The temperature of the melt was then raised above liquidus temperature and finally it was poured into the cast iron permanent mould of 16mm diameter and 170mm height. For the comparison study, the composites were subjected to heat treatment in a muffle furnace and microwave furnace separately and then followed by electric discharge machining.

2.3 Heat Treatment

The main purpose of the heat treatment of the composite is to improve the composite properties in an economic way. Both conventional and microwave heat treatment on the composites were employed in this study. In the conventional heat treatment B₄C and graphite particles could not affect the heating mechanism. However, B₄C and graphite are good absorbers of microwave energy. In conventional heat treating process, energy is transferred to the material from the surface of the material whereas in microwave heating, the energy is directly delivered to material through the molecular interaction with the electromagnetic field [8]. Microwave heating process improves the product uniformity by providing unique microstructure and properties that are results of selective heating. Conventional heat treatment was carried out in a muffle furnace at 520°C for 509 minutes. Figure.1. shows microwave heat treatment set up. 850W Microwave furnace was used for heat treatment of the composite. In order to obtain T6 property of Al-6061 alloy, solution heat treatment was done over the material and it was heated up to 520°C in the microwave oven. The composite was heat treated in microwave furnace for 198 minutes and then cooled in furnace itself.
2.4 Mechanical testing

Hardness is the resistance of a material to abrasion. The hardness tests were conducted in Rockwell hardness tester with Steel ball indenter (1/16 inch) and a load of 100 kgf. The load was applied for 30 seconds and the hardness of the composite was found out at different places and average value is reported.

The impact toughness of a material can be determined by impact test. The impact tests were conducted in Izod Impact tester. The size of the specimen was 75mm x 10mm x 10mm, and a notch of 2mm. Figure 2 shows typical specimens before and after impact test.

2.5 Electric Discharge machining

A copper electrode of 14.7 mm diameter was used as anode and the fabricated composite was used as cathode in the machining process. The current density, pulse on-time, pulse off-time were the input parameters of the machining process. Current is varied from 6, 9 and 12 ampere, likewise pulse on-time and pulse off-time is varied from 36, 48, 56 and 7, 8, 9 microsecond respectively. The EDM setup is shown in figures 3 and 4.
The supply of dielectric fluid (EDM Oil) is given by means of suitable arrangement. The material removal was enabled by a spark generated between the tool (anode) and the work piece (cathode). A constant gap of 0.005 – 0.05mm was maintained by means of a servo motor.

3. Results and Discussions

3.1 Micro structural Examination

Figure 5 shows the microstructure of Al6061-boron graphite composites. Micrographs reveal that there was a fairly uniform distribution of boron carbide and graphite particulates throughout the matrix alloy and exhibited lower porosity. It is also reported that higher hardness is always associated with lower porosity of the MMCs. It can be observed that there is good bonding between the matrix and the reinforcement particulates resulting in better load transfer from the matrix to reinforcement material.

![Microstructure of Al6061- Boron Carbide Graphite composites](image)

3.2 Mechanical properties

The hardness and impact strength values of the composite material during conventional and microwave heat treatment are presented in table 5. Comparable results were obtained in both cases and the deviation was not significant.

| Property                  | Conventional heat treatment | Microwave heat treatment |
|---------------------------|-----------------------------|-------------------------|
| Hardness(HRC)             | 63                          | 67                      |
| Impact strength(J/mm²)    | 0.16                        | 0.18                    |

3.3 Electric discharge machining

The composite material was machined for parameters of current, pulse on time and pulse off time [9]. The response parameters such as material removal rate and tool wear rate were determined for conventional and microwave heat treatments. The experiment was conducted based on the L9 orthogonal array [10]. The material removal rate and tool wear rate in table 6 shows a comparable set of values for conventional and microwave heat treated composites.
Table 6 Experimental results

| Current (A) | Pulse on time(μs) | Pulse off time(μs) | Conventional heat treatment | Microwaves heat treatment |
|-------------|-------------------|--------------------|----------------------------|--------------------------|
|             |                   |                    | MRR (g/min) | TWR (g/min) | MRR (g/min) | TWR (g/min) |
| 6           | 36                | 7                  | 0.04221     | 0.000356    | 0.022288    | 0.00106     |
| 6           | 48                | 8                  | 0.05487     | 0.0243      | 0.09952     | 0.00062     |
| 6           | 56                | 9                  | 0.05164     | 0.000231    | 0.10284     | 0.00066     |
| 9           | 36                | 8                  | 0.15326     | 0.001374    | 0.15286     | 0.00046     |
| 9           | 48                | 9                  | 0.16992     | 0.00451     | 0.1864      | 0.00052     |
| 9           | 56                | 7                  | 0.14583     | 0.001953    | 0.14952     | 0.00056     |
| 12          | 36                | 9                  | 0.28253     | 0.00351     | 0.21105     | 0.000625    |
| 12          | 48                | 7                  | 0.22450     | 0.003921    | 0.20184     | 0.00036     |
| 12          | 56                | 8                  | 0.22028     | 0.001932    | 0.2041      | 0.0003      |

The results obtained from table 6 were analyzed and the optimal parameter combination for each type of heat treatment can be found out from the respective graphs. Interaction graphs for one and two factors are depicted in figures 6. It is observed that the material removal rate increases with an increase in current and pulse on time, whereas it is found to decrease on increasing pulse off time, as the effective sparking time is reduced. The optimal parameters for increased MRR and reduced TWR can be deduced from the graphs shown in figure 7.

Current increases the power of the plasma produced, thereby increasing the MRR. The pulse on time increases as the spark plasma sustains for a long time to reach the sub layer of MMC resulting in increased MRR. Longer pulse off time results in the sparks taking longer time to reinitiate and MRR is reduced. However it is understood from the table 5, that the hardness of the microwave heat treated composite is increased to some extent due to microwave interaction with boron carbide and graphite leading to volumetric heating and also microwave couples with porous areas because of high dielectric constant resulting in closure of porous sites. Due to increased hardness of the microwave heat treated MMC, the impact of current and pulse on time on MMCs is evident.

It is also noted that the MRR decreases marginally when compared to conventionally heat treated MMCs, in some process parameter conditions. It is noteworthy that microwave interaction takes very less time in MMCs leading to fine dispersion of precipitates. Conversely, in conventionally heat treated MMCs it is believed that coarse grain or grain growth occurs due to longer processing time. Hence hardness in microwave heat treated MMCs are comparable to that of conventionally heat treated MMCs. It is understood from the experimental results that MRR and TWR values obtained from both the heat treatment methods were closer in almost all EDM process parameters. Hence selection of the heat treatment process for electric discharge machining should be judiciously done by the operator.
Fig. 6 Variation of MRR with input parameters for conventional heat treatment
4. Conclusion

Aluminium–B₄C–graphite composites were successfully fabricated by two step stir casting method in an economic way. The distribution of graphite and boron carbide on the matrix was fairly uniform, showing a reduced porosity and a good bonding between the matrix and the reinforcements. Microwave heat treatment proved to be an effective and energy efficient way in comparison to that of conventional heat treatment. The time and the energy utilized were significantly low in the case of microwave heat treatment without any appreciable loss in the properties of the composite, which was machined by performing electric discharge machining for various parameters and levels. It is found that current and pulse on time is the most influential parameters in both conventional and microwave heat treatment.

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