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Experimental investigation and mathematical modelling for material removal and tool wear in making of rectangular channels by Electric Discharge Machining (EDM) on Aluminium-Boroncarbide composite sintered preforms.

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Boron carbide (B_4C) particulate Aluminum (Al) Metal Matrix Composites (MMCs) are highly demanded due to their specific strength in aerospace, defense and nuclear sectors. The controllable porosity which causes for the good toughness and the forming limit values can be obtained for these MMCs synthesized by powder metallurgy route. But the porosity level had great influence on the machinability of these MMCs by Electric Discharge Machining (EDM). In the present work, cold compaction followed by sintering of Al and B_4C powders were used to fabricate the MMC specimen. The density and hardness were estimated by archimedes principle and Vickers micro-hardness test respectively. The feasibility of EDM of the fabricated MMC at high porosity level (19%) was evaluated through pilot experimental runs. The full factorial experimental design with three parameters of three levels each (total runs 3^3=27) used for experimentation. Each experiment used a fresh copper electrode of thickness 1 mm to make the rectangular channel on the MMC specimen. The influence of electrical process conditions such as discharge current (I), pulse-on duration (T-On) and pulse-off duration (T-Off) on Material Removal Rate (MRR) and Tool Wear Rate (TWR) were studied. A mathematical model was formulated to represent the process. Analysis of variance (ANOVA) was performed to identify the significant parameters effecting the Material Removal Rate (MRR) and Tool Wear Rate (TWR). Results revealed that the developed model was adequate to represent the process with R-square values of 94.9%, and 83.82% for MRR and TWR respectively. Results also shown that the discharge current had a significant effect on the MRR and TWR.

***Keywords*:** B_4C, Porosity, Electric Discharge Machining (EDM), Material Removal Rate (MRR).

1. Introduction

The specific mechanical properties of Al-B_4C particulate MMCs are highly appreciable in the high technology industries such as nuclear, friction and computer hard discs.[1] They are also identified as a potential materials in the field of defence armour components and aerospace [2–4]. These MMCs had a great flexibility during processing by solid state powder synthesis route to achieve significant improvement of required property in the specified application. The flexibility in terms of varying processing conditions which effect the desired property were explored by researchers [5]. The effect of compaction pressure, sintering temperature and milling time on density and bending strength of these MMCs (Al-10wt.B_4C) were extensively studied by Abinojar et al. [6]. Authors suggested that the optimum alloying time, pressure and temperature as 12 hours, 700MPa and 635℃ respectively. Mohanty et al. [7] explored the effect of weight proportion of the B_4C particles in the range of 0-25% for density, electrical conductivity, hardness and flexural strength. Authors concluded that the hardness and strength were improved with some embrittlement by increasing the B_4C weight fraction but electrical conductivity decreased. Karako [8] studied the effect of B_4C wt.% on mechanical properties and suggested the 10wt.% and 5wt.% for improved fracture toughness and tensile strength respectively. Authors also conducted some conventional machinability studies for good surface finish and machining properties. Weber et al. [9] experimented for electrical conductivity and density values of Al-MMCs at various shape, size and volume fraction of Al_2O_3 particulates. Authors concluded that the electrical conductivity decreased with increased volume fraction of Al_2O_3 but the equiaxed spherical shape of Al_2O_3 reduces the same compared to an angular shape. Chang et al. [10] developed models to predict the electrical resistivity of the MMCs and compared experimentally. The high temperature mechanical properties are also witnessed by Onoro et al. [11] of Al alloy- B_4C MMCs. The tremendous improvement in mechanical properties of Al-15wt.% B_4C-1.5wt.% Co MMC was also reported by Ghasali et al. [12].

The machinability studies of these MMCs by conventional machining methods are also found rarely. Moreover those methods phasing challenges because of the presence of hard B_4C particles such as premature failure of the cutting tool, high temperature at work- cutting tool- chip interfaces, fluctuation in cutting forces, worn out cutting tool profile geometry, dimensional inaccuracy and lack of surface integrity of the finished product [13]. Therefore a non-conventional method, electric discharge machining (EDM) is being reported as a potential process to overcome these limitations while machining of MMCs. In EDM the material removal takes place by precisely controlled sparks that occur between a tool (electrode) and a work-piece separated with a specific small gap (spark gap) in the presence of a dielectric fluid such as hydrocarbon oil or de- ionized water. Vaporization of work material occurs due to intensive heat of generated spark (high frequency) between tool and work electrodes for a very short span of time (micro seconds). Non-contacting type, low MRR during EDM/ Micro EDM process is attributed to attain high surface finish and dimensional accuracy [14–16].

From the reported literature it was observed that the level of porosity and the volume/ weight fraction of B_4C particles had a great impact on the electrical, thermal and mechanical properties of the MMCs. The high level porosity and unavoidable changes in the electrical conductivity in the fabricated MMCs by this powder metallurgy route will affect the machining (EDM) performance [17]. However, the porous structure had an advantage of removing high heat flux in various thermal management application systems [18]. Therefore, the present study conducted to check the feasibility of EDM of the high porous (19%) Al-6Wt.% B_4C MMC and to optimize the process conditions to improve MRR.

2. Materials and Methods

2.1 fabrication of MMC work specimen and tool electrode

Pure aluminium in the powder form of 325 mesh (99.9% pure, SRL laboratory) and the B_4C particles of average size 35µm (99.9% pure, Supertek dies, Delhi.) were used as matrix and reinforcement (RF) phases respectively. The scanning electron microscope image and X-ray diffraction pattern of B_4C particulates were shown in the Fig. 1a and Fig. 1b. The B_4C particulates of 6 weight percentage (wt.%) were added to the Al powder particles and mixed thoroughly in a ceramic bowl manually for 30 minutes. The matrix and RF particle mix was compacted (cross section of 30 mm×30 mm) at room temperature in the metallic die under 500 kN capacity hydraulic press. The loading rate and dwell during compaction were set as 1 mm/ sec and 90 minutes respectively till the pressure of 280 MPa achieved. The compacted green specimen was sintered in a tubular furnace under argon atmosphere. The theoretical and experimental density of the sintered MMC specimen were measured by a rule of mix and archimedes principle. The hardness (HV) was measured by vicker's microhardness test (model: Economet VH 1MD) at a load of 100 g with dwell about 10 s. The microstructure was studied under the optical microscope (Model HUVITZ LUSIS HC-30MU). The XRD pattern of the MMC specimen compared to the pure Al was shown in Fig. 1c. The photographs of die, hydraulic press setup and compacted MMC specimen were shown in Fig. 2. The sintering of MMC was carried out under argon atmosphere in tubular furnace. The sintering cycle consist of heating the MMC at rate of 2 ℃/ min up to 100 ℃ (hold for 20 minutes), 1.5 ℃/ min upto 250 ℃ (hold for 10 min), and 7 ℃/ min up to 600 ℃ (hold for 90 min) followed by furnace cooling (approximately 270 min.)

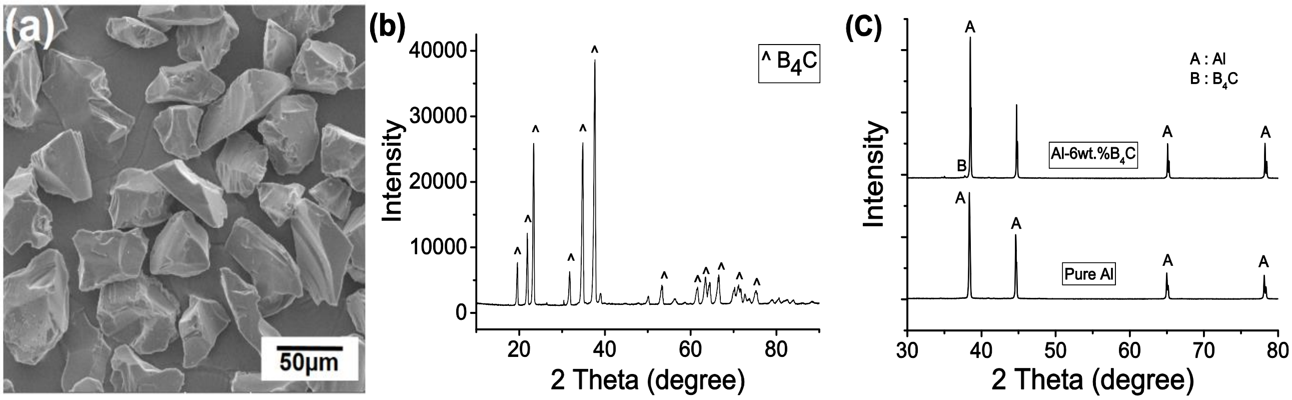

Fig. 1a. SEM micrograph of B_4C particulates, b. XRD pattern of B_4C, c. Comparison of XRD pattern of pure Al and Al-6wt.% B_4C

2. 2. Experimental- Sinker EDM of rectangular channel

The diesinker EDM machine (Model PSR-20, Ratnaparki, India.)was used to make the rectangular channels in the fabricated Al-6wt.% B_4C MMC specimen. The tool material made of copper (Cu) of 1 mm thickness was precisely machined through wire-EDM. The average surface roughness of the tool electrode and MMC work specimen were measured with surface profilometer (Model: Taylor Hobson Surtronic S128) as 1.02 µm and 1.03 µm respectively. The tool- work arrangement of positive polarity was continuously flushed with commercial EDM oil as a dielectric. Tool electrode was vertically fed towards the work till it reaches the spark discharge gap of 0.25 mm. At this stage a high electric potential (105 ± 10 V) was applied to initiate the plasma in the spark gap by the breakdown of dielectric. The discharge voltage was maintained of the value 55 ± 10 V. As a result, melting and vaporization of the work material were occurred due to the intensive heat of generated plasma (high frequency) in a very short span of time (micro seconds). Hence, the crater was created on the work specimen which replicate the shape of the tool electrode. Pilot experimental runs were conducted based on the available specifications of the EDM setup to fix the range for input experimental conditions. The varied input parameters with their levels and the full factorial experimental design were represented in the Table 1 and Table 2 respectively. The present study considered the material removal rate (MRR) and Tool Wear Rate (TWR) for fixed machining time of 2 minutes as a response variables. MRR and TWR were estimated by the weight difference before and after machining of unit time upon the measured density. The photographs of the tool (Cu) and work specimens of EDM machined slots were shown in Fig. 2.

Table. 1. Representation of experimental conditions.

Fixed parameters	
Polarity	: Straight, (Positive)
Spark open voltage	: 105 ±10
Discharge gap voltage	: 65V
Tool electrode	: Cu
Machining time	: 2 min
Work	: Al-6wt%B_4C MMC
Thickness of the tool	: 1.00 ± 0.04 mm

Varied parameters and their levels			
Factor code, Parameter	Level 1	Level 2	Level 3
A. Discharge current, I (A)	4	6	8
B. Pulse duration on time, T-on (μs)	25	45	65
C. Pulse duration off time, T-off (μs)	24	36	48
Performance output (response variable)			
Response variable 1	: Material Removal Rate, MRR (mm^3/min)		
Response variable 2	: Tool Wear Rate, TWR (mm^3/min)		

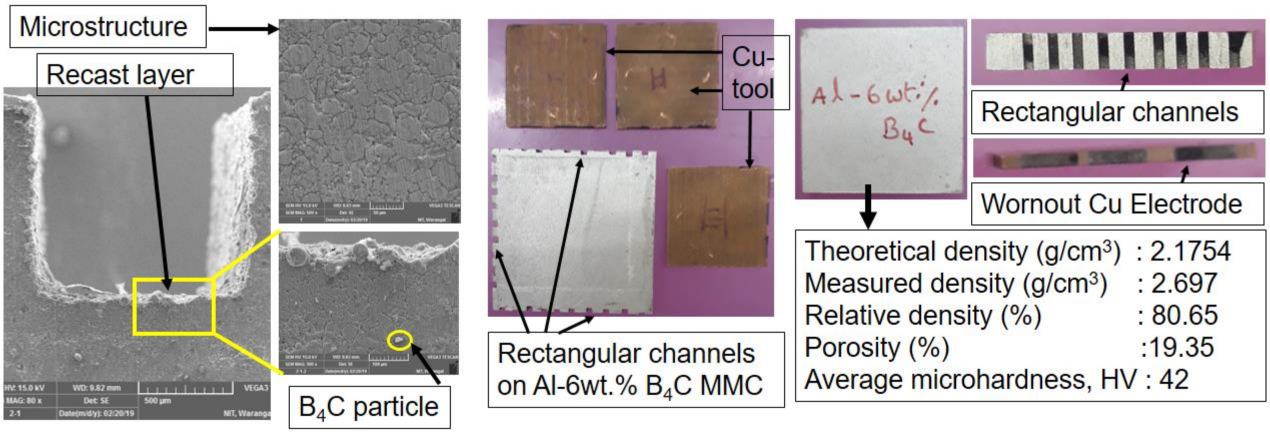

Fig. 2. Photographs and SEM micrographs of Al-6wt.% B_4C MMC and Cu-tool.

3. Results and Discussion

The full factorial experimental representation for response values were shown in Table 2. The regression equation were developed to represent the process for the responses and ANOVA was performed. The multiple regression coefficients of the developed models indicate that the model can explain variation in MRR and TWR to the extent of 94.90% and 83.82% respectively. Thus the developed mathematical models are adequate to represent the EDM process. ANOVA revealed that the discharge current having p-values as 0.000 and 0.007 for both the MRR and the TWR respectively. Hence, the discharge current is the most significant parameter effecting the both responses. The main effect and interaction plots for MRR and TWR were shown in Fig. 3 and Fig. 4 respectively. From these plots it was observed that the high discharge current values improve the MRR and TWR. The reason is the amount of heat energy transferred to both the tool and work increases as current increases.

Table. 2. Representation of full factorial experimental design.

Standard Order	Run order	Factor, A Current (A)	Factor B, T- On (μs)	Factor C, T- Off (μs)	Response 1 MRR(mm^3/min)	Response 2 TWR(mm^3/min)
10	1	6	25	24	2.119	0.065
22	2	8	45	24	3.188	0.091
13	3	6	45	24	2.328	0.049
3	4	4	25	48	0.995	0.006
21	5	8	25	48	2.572	0.117
23	6	8	45	36	2.508	0.013
14	7	6	45	36	1.655	0.085
1	8	4	25	24	1.203	0.04
4	9	4	45	24	0.618	0.06

27	10	8	65	48	2.954	0.103
6	11	4	45	48	1.331	0.036
19	12	8	25	24	2.137	0.099
12	13	6	25	48	2.248	0.089
26	14	8	65	36	2.995	0.038
9	15	4	65	48	0.379	0.015
16	16	6	65	24	1.462	0.038
18	17	6	65	48	1.308	0.036
5	18	4	45	36	0.731	0.001
2	19	4	25	36	1.117	0.017
24	20	8	45	48	2.867	0.109
15	21	6	45	48	1.898	0.061
25	22	8	65	24	1.894	0.075
20	23	8	25	36	2.071	0.075
17	24	6	65	36	1.386	0.031
7	25	4	65	24	0.402	0.026
8	26	4	65	36	1.016	0.069
11	27	6	25	36	1.17	0.045

Regression Equation for MRR

$MRR = 1.41 + 0.127\,A + 0.0163\,B - 0.0895\,C - 0.0024\,A^2 - 0.000669\,B^2 + 0.00101\,C^2 + 0.00538\,A{*}B + 0.00240\,A{*}C + 0.000183\,B{*}C$

Table. 3. ANOVA for MRR

Source of variation	Degree of freedom	Sum of square	Mean square	F-Value	P-Value
Model	18	16.4353	0.9131	8.27	0.002
Linear	6	13.9891	2.3315	21.13	0.000
A	2	13.1658	6.5829	59.66	0.000
B	2	0.6175	0.3088	2.80	0.120
C	2	0.2058	0.1029	0.93	0.432
2-Way Interactions	12	2.4462	0.2039	1.85	0.195
AB	4	0.8620	0.2155	1.95	0.195
AC	4	0.6252	0.1563	1.42	0.312
BC	1	0.9590	0.2397	2.17	0.163
Error	8	0.8827	0.1103		
Total	26	17.3181			

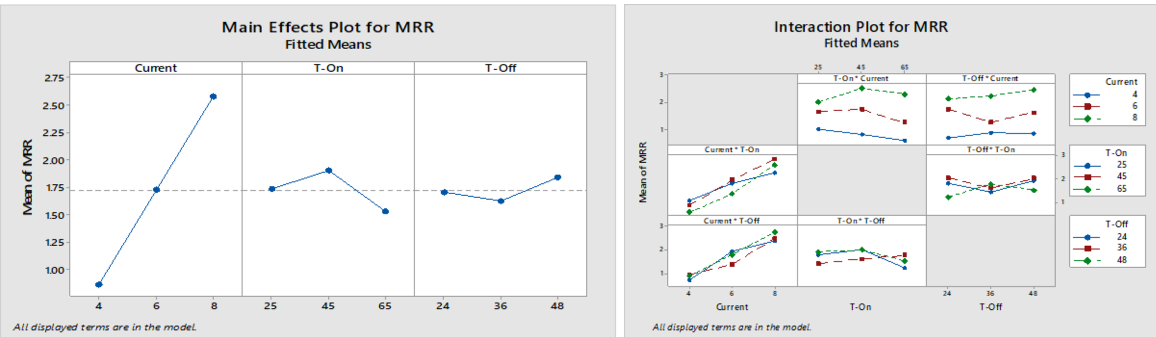

Fig. 3. Main effect and interaction plots for MRR

Regression Equation for TWR

$$TWR = 0.185 + 0.0087\ A + 0.00143\ B - 0.01294\ C - 0.00011\ A^2 - 0.000004\ B^2 + 0.000142\ C^2 - 0.000255\ A*B + 0.000463\ A*C + 0.000003\ B*C$$

Table. 4. ANOVA for TWR.

Source of variation	Degree of freedom	Sum of square	Mean square	F-Value	P-Value
Model	18	0.024061	0.001337	2.30	0.115
Linear	6	0.014622	0.002437	4.20	0.033
A	2	0.011241	0.005621	9.68	0.007
B	2	0.000842	0.000421	0.73	0.513
C	2	0.002539	0.001269	2.19	0.175
2-Way Interactions	12	0.009438	0.000787	1.36	0.341
AB	4	0.002739	0.000685	1.18	0.389
AC	4	0.005643	0.001411	2.43	0.133
BC	1	0.001056	0.000264	0.45	0.767
Error	8	0.004643	0.000580		
Total	26	0.028704			

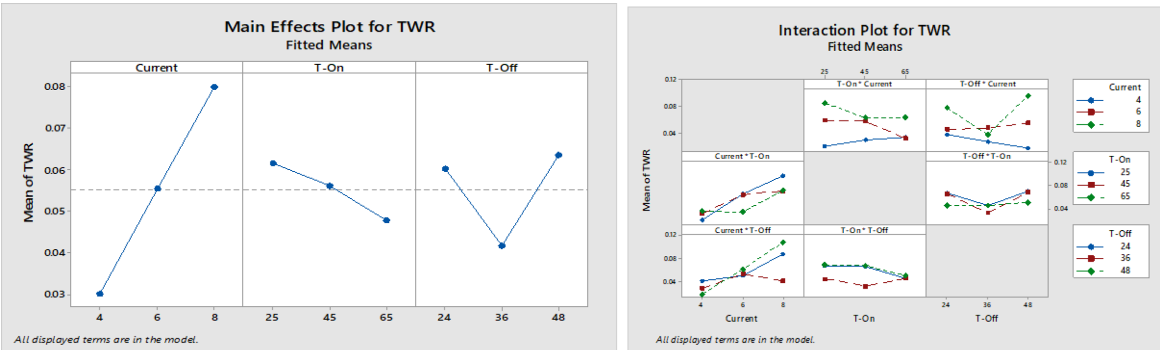

Fig. 4. Main effect and interaction plots for TWR

3. Conclusions

The Al-6wt.% B_4C composite was successfully fabricated by powder synthesis route. The porosity (due to choice of fabrication method and conditions) and the electrical conductivity (due to less conductive B_4C particle inclusion) of the composite affect the EDM. The reason is the discharge phenomenon directly affected by electrical conductivity of the tool and the work material. The porosity level and the size distribution of pore in the composite will affect the crater volume and debris evacuation from the machining zone. Hence the present study proved that the machining of these MMCs by EDM is possible. Results revealed that the developed model was adequate to represent the process.

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