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Machinability of B_4C-reinforced Al2014 metal matrix composites in electric discharge machining

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ABSTRAC: This study was conducted to clarify the effect of various variables such as the type of electric discharge machining, discharge current and reinforcement content of B_4C-reinforced Al alloy metal matrix composite on workpiece removal rate, electrode wear rate and material removed per discharge pulse, which are not extensively explored in the literature. B_4C-reinforced Al2014 matrix composite samples containing 5 and 10 vol.-% B_4C particles, produced by vacuum infiltration method, were machined with electric discharge machining and powder mixed electric discharge machining at various discharge current settings. In both types of machining processes, the workpiece removal rate and electrode wear rates decreased and increased, respectively, when the reinforcement contents of the composites increased. However, powder-mixed electric discharge machining enhanced the machining stability, and a comparatively higher workpiece removal rate was observed with a decreased electrode wear rate. On the other hand, by increasing the discharge current, which was also verified as the most effective machining parameter in variance analysis, both workpiece removal rate and electrode wear rate values increased in both machining techniques. The experimentally calculated volumetric workpiece material removed by a discharge pulse was compared to that of a model in the literature, and they were also found to be consistent with each other.

KEYWORDS: Al2014; B_4C; Metal matrix composite; Powder mixed electric discharge machining; Vacuum infiltration

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RESUMEN: *Maquinabilidad por electroerosión de materiales compuestos de matriz de aluminio Al2014 reforzados con B_4C.* Este estudio se llevó a cabo para aclarar el efecto de varias variables, como el tipo de mecanizado por electroerosión, la corriente de descarga y el contenido de refuerzo del compuesto de matriz metálica de aleación de aluminio reforzado con B_4C sobre la tasa de eliminación de la pieza de trabajo, la tasa de desgaste del electrodo y el material eliminado por pulso de descarga, que no son ampliamente explorados en la literatura. Muestras compuestas de matriz Al2014 reforzada con B_4C que contienen 5 y 10 vol. El % de partículas de B_4C, producidas por el método de infiltración al vacío, se mecanizaron por electroerosión y por electroerosión con mezcla de polvo con varios ajustes de corriente de descarga. En ambos tipos de procesos de mecanizado, la tasa de eliminación de piezas de trabajo y las tasas de desgaste de los electrodos disminuyeron y aumentaron, respectivamente, cuando aumentó el contenido de refuerzo de los materiales compuestos. Sin embargo, el mecanizado por electroerosión con mezcla de polvo mejoró la estabilidad del mecanizado y se observó una tasa de eliminación de piezas de trabajo comparativamente más alta con una tasa de desgaste de electrodos más baja. Por otro lado, al aumentar la corriente de descarga, que también se verificó como el parámetro de mecanizado más efectivo en el análisis de varianza, tanto la tasa de eliminación de piezas como la tasa de desgaste de los electrodos, aumentaron con ambas técnicas de mecanizado. El material volumétrico de la pieza de trabajo, calculado experimentalmente, eliminado por un pulso de descarga, se comparó con el de un modelo en la literatura, y también se encontró que eran consistentes entre sí.

PALABRAS CLAVE: Al2014; B_4C; Compuesto de matriz metálica; EDM mezcla de polvo; Infiltración al vacío

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1. INTRODUCTION

Ceramic particle-reinforced metal matrix composites (MMCs) are difficult to machine with conventional machining methods because of excessive cutting tool wear. That said, MMCs with sufficient electrical conductivity can be successfully machined using the non-traditional process of electric discharge machining (EDM). The B_4C reinforced MMCs are preferred in applications where lightness and high wear resistance are required. Yet, studies on B_4C-reinforced Al matrix composites are rare compared to SiC and Al_2O_3-reinforced counterparts. This can be attributed to high production costs and difficulties encountered during EDM because of decreased electrical conductivity introduced by increased reinforcement volume percentage (RP).

Solid-state powder metallurgy (P/M) is one of the most widely used methods in producing MMCs. The key drawbacks of this technique are the need for secondary processes, the geometry limitations of the part, and high production costs. Several studies have used the P/M method containing cold compaction and sintering to obtain B_4C-reinforced Al matrix composites (Bodukuri *et al.*, 2016; Çelik and Seçilmiş, 2017). These studies revealed that the hardness of composites increases as RP increases due to the increasing content of hard ceramic powders. The unavoidable residual porosity in the composite is viewed as a key disadvantage. Liquid processing techniques such as stir casting have also been used to produce B_4C-reinforced Al matrix MMCs (Ravi *et al.*, 2015). Increased RP increases the microhardness and tensile strength of the composites, but high B_4C content increases the viscosity value of the liquid matrix, making processing difficult to provide homogenous reinforcement distribution.

The use of the vacuum infiltration technique yields significant advantages in the economics of MMCs production. Among the strengths of this technique are the relative simplicity and the application without needing high technologies. Furthermore, it is noted that the sufficient wettability between liquid matrix and reinforcement particles during production yields a notably high performance of the composites. In order to obtain MMCs with the desired properties, the temperature and pressure values were kept in the range of 700 °C–850 °C and 400 mmHg–600 mmHg, respectively (Pul, 2010). In the studies in which the matrix materials are chosen as Al alloy or Mg, the processing variables are tried to be optimized to obtain MMCs with the highest hardness and homogeneous reinforcement particle distribution (Aksöz *et al.*, 2014; Yantao and Chen, 2014). However, there is still a need for further improvement of the technique, particularly (i) to get Al alloy matrix composites with low porosity, (ii) to obtain a homogenous distribution of reinforcement particles, and (iii) to get the optimum content of reinforcement particles. These improvements are essential to increase the machinability of the composite by EDM since machining of B_4C reinforced MMCs is hard, especially at high B_4C contents, wherein the B_4C particles have low electrical conductivity.

There are several studies about EDM of Al/Al alloy matrix composites reinforced with particles such as SiC (Hocheng *et al.*, 1997; Müller and Monaghan, 2000; Singh *et al.*, 2004; Dhar *et al.*, 2007; Kathiresan and Sornakumar, 2010; Gopalakannan *et al.*, 2013; Kumar *et al.*, 2014; Prasanna *et al.*, 2017; Manish and Dhakad, 2018; Naik *et al.*, 2020; Naik *et al.*, 2022), red-sludge (Kar *et al.*, 2018), TiB (Prabu *et al.*, 2013; Senthil *et al.*, 2014), B_4C (Kumar *et al.*, 2014; Manish and Dhakad, 2018) and Al_2O_3 (Radhika *et al.*, 2014; Kandpal *et al.*, 2018). The studies were primarily conducted to reveal the effects of EDM parameters on the machining performance outputs such as workpiece removal rate (WRR), electrode wear rate (EWR), surface roughness, surface integrity and hole overcut. The critical study parameters were pulse time t_s, discharge current I_d, type of electrode and dielectric, and RP. Some of the studies developed a mathematical model (Dhar *et al.*, 2007), a multi-response optimization technique (Senthil *et al.*, 2014; Naik *et al.*, 2020) and used the Taguchi and Box–Behnken design methods (Gopalakannan *et al.*, 2013; Radhika *et al.*, 2014; Prasanna *et al.*, 2017; Kandpal *et al.*, 2018; Naik *et al.*, 2020; Naik *et al.*, 2022) and fuzzy logic analysis (Gopalakannan *et al.*, 2013; Kumar *et al.*, 2014; Manish and Dhakad, 2018) to estimate the optimum EDM parameters maximizing the performance outputs. Although it is possible to optimize the processing variables in EDM, the ceramic reinforcement content should be kept as low as possible since it decreases the electrical conductivity, resulting in an unstable machining regime, low WRR, high EWR and poor surface quality. Some studies on EDM of MMCs, referred to as powder mixed EDM (PM/EDM), tried to eliminate the encountered problems by adding a conductive powder to the dielectric fluid such as graphite powder or Cr powder (Sidhu *et al.*, 2014; Dubey and Singh, 2018). The PM/EDM increases the electrical conductivity of dielectric fluid by creating conductive powder bridges between the workpiece and tool electrode. Higher electrical conductivity of the dielectric fluid slightly increases the performance outputs. However, there is still a need for further optimization for EDM of MMCs due to the decreased in the electrical conductivity when the ceramic reinforcement particle content is increased.

In light of the studies summarized above, we determined that there is no notable research published about B_4C reinforced Al matrix MMCs, produced by the vacuum infiltration method, particularly investigating the effect of; i) machining with EDM and PM/EDM, ii) I_d and RP on machining performance outputs, and iii) I_d, RP and machining type (EDM, PM/EDM) on workpiece material removed per discharge pulse (WRD). Accordingly, in this study, B_4C (5 and 10 vol.%) reinforced Al2014 matrix MMCs were produced by vacuum infiltration and machined with EDM and PM/EDM to obtain the variation of machining performance outputs with RP and type of machining. Microstructural examination of MMCs after production has been carried out to reveal the distribution of B_4C powder particles with their interface characteristics. The pin-on-disc abrasion tests were carried out to find the composites' abrasion weight loss and wear coefficient values. WRR and EWR were also examined by applying EDM and PM/EDM using various machining variables. Variance analysis and F-test were performed to determine the experimental results' reliability and the importance of machining parameters on performance outputs. The WRD values found from experiments and a model for EDM conditions were compared for different I_d and RP values.

As for the structure of this paper, the Materials and Methods (Section 2) covers the production methodology of the samples, the abrasion test procedure, the EDM and PM/EDM machining settings, the calculation of the MRR and EWR values, the methodology and calculation assumptions of the experiment, and the model WRD values. The Results (Section 3) will provide the findings about the friction and abrasion characteristics of the samples, the effects of RP and EDM and PM/EDM machining settings on machining performance outputs, the test results of ANOVA and F-test, and a comparison of experimental and theoretical (model) WRD values. The essential findings, concluding remarks, and suggestions about future work will be presented in the Conclusions (Section 4).

2. MATERIALS AND METHODS

Al2014 alloy (Table 1) was used in the study as a matrix and B_4C powders (Table 2) as reinforcement material in the MMCs. The average particle sizes of the as-received Al2014 alloy and B_4C powders, supplied from Nanografi Nano Technology Company (Ankara), were 290 µm and 70 µm, respectively. The Al2014-B_4C powder mixtures containing 5% and 10% B_4C particles by volume were mixed for 30 minutes using a 3D Turbula mixer. Powder mixtures are then filled into 70 mm long quartz tubes with an outer diameter of 10 mm and an inner diameter of 9 mm. The bottom parts of the tubes are closed with a stainless-steel filter. An aluminum foil is placed on the steel filter to prevent powder from spilling. Dry silicon sand is also placed on top of the steel filter placed on top of the powder to prevent the upward movement of powder during vacuum infiltration. Another filter was placed on the sand to prevent sand from moving upwards during vacuum application. A heat-resistant filter is put on the upper opening of the tubes to ensure sealing between the vacuum unit and the powders. The Al2014 alloy kept molten at 750±5 °C in the melting pot was then vacuum infiltrated into the tube at 550±10 mmHg pressure. At least six samples were produced for composites containing 5% and 10% B_4C particles by volume. After production by infiltration method, the composite samples' microstructures were examined by Nicon Eclipse LV150N microscope at their cross-sections to reveal the underlying microstructure and the distribution of B_4C particles.

Table 1. Chemical composition of Al2014 alloy (wt.%)

Al	Cu	Si	Mn	Mg	Cr
93.5	4.4	0.8	0.6	0.5	0.1

Table 2. Chemical composition of B_4C (wt.%)

B	C	Fe	Si	Ca	Cl	F
80	18.1	1.0	0.5	0.3	0.075	0.025

Pin-on-disc abrasion tests (10 N load, 200 rpm rotation speed, 50 mm rotation dia, 100 m sliding distance) were performed to investigate the effect of RP on the abrasion behavior. The tests were repeated three times for averaging.

The EDM and PM/EDM experiments were carried out using the Charmilles D20 machine. Electrolytic copper with a diameter of 10 mm and a length of 25 mm was used as a tool electrode (- polarity). The 70 mm long MMC samples were sliced to 5 mm by wire EDM. Kerosene dielectric with side flushing (0.1 MPa pressure) was used in EDM and PM/EDM experiments. Graphite powder (1.5 W cm^{-1} K^{-1} thermal conductivity, 3×10-3 μΩ cm^{-1} electric conductivity) with 20 μm average size with a concentration of 10 g·L^{-1} (C_g) was used in PM/EDM experiments. The machining settings used in the experiments were I_d =2, 4, 8 A, t_s=8 μs and pause time t_p =1 μs. The selected t_s and I_d values are commercially used settings. The I_d values above 8 A result in poor surface finish, and lower than 2 A causes a long machining time. t_s=8 ms yields a good surface finish. Lower settings result in a long machining time. The RP value higher than 10% was not used since it causes EDM and PM/EDM machining instabilities due to the low electrical conductivity of samples.

WRR (g/min) and EWR (g/min) were calculated by dividing the weight loss of the workpiece and the electrode by the machining time corresponding to a 2 mm depth of machining, respectively. The experiments were repeated three times for result averaging. The machined samples' surfaces were examined to reveal the effect of EDM and PM/EDM techniques on surface texture. Variance analysis (ANOVA) and F-test were performed using Minitab v18 software to determine the experimental results' reliability and the importance of machining parameters on performance outputs.

The WRD in mm^3/discharge for the machining parameters was calculated using these experiment outcomes and a model developed for a single discharge pulse in EDM by Sarıkavak and Çoğun (2012). The plasma channel was assumed to be uniform and cylindrical. The heat losses from the plasma channel were neglected. Eq. (1) was used to calculate the plasma radius R_p (Ikai and Hashiguchi, 1995):

$$R_p = 0.00204 I_d^{0.43} t_a^{0.44} \qquad (1)$$

A constant temperature was assumed on the workpiece surface during . Heat transfer between the heat source and the workpiece was by conduction. The model assumed that the workpiece material reached the melting temperature (T_m) of the material and was removed from the surface. The thermal or mechanical property of the composites used in the model was calculated using the rule of mixtures. The numerical solution of the model was obtained using the finite element solver ANSYS Workbench v.20 software. The discharge voltage (V_d) for the used pulse generator was 23 V. The plasma channel power , given in Eq. (2), was inputted into the model to find the workpiece temperature distribution suggested in the Sarıkavak and Çoğun (2012) study.

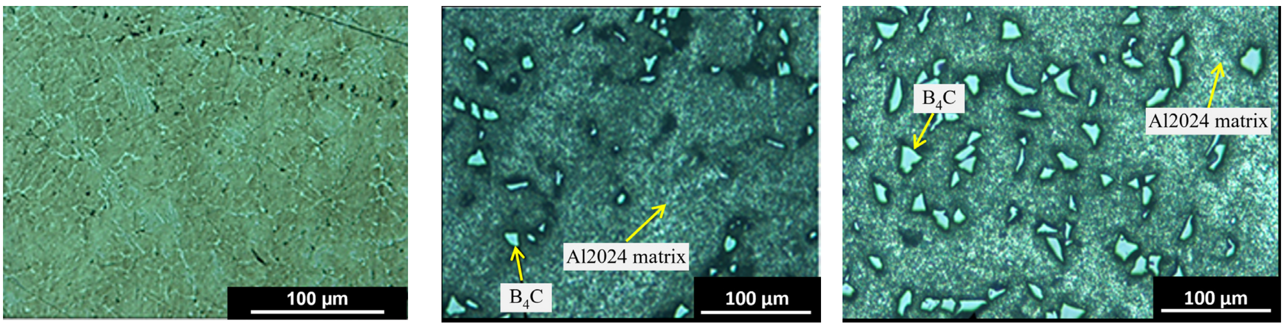
$$P_p = I_d V_d \qquad (2)$$

3. RESULTS

The B_4C reinforcement particles were homogeneously distributed in the Al2014 matrix of MMCs (Fig. 1b-c). Sufficient wetting was achieved between the reinforcement and the matrix, as no visible porosity or micro-cracks were formed at the interface regions.

The coefficient of friction values measured for each sample with the same amount of reinforcement was almost constant throughout the tests due to the homogenous distribution of B_4C particles in the composite matrix (Fig. 2). The measured coefficient of friction values increased as more B_4C particles were added to composites (Fig. 3). However, as expected, the abrasion weight loss values decreased since the quantity of hard B_4C powders increased in the matrix, leading to less abrasion during the test (Fig. 4).

An unstable machining regime was observed as the RP increased in the composites. In the PM/EDM experiments, the machining stability was better and WRR values were higher than in EDM experiments (Fig. 5a). The highest WRR was obtained at the maximum value of 8 A in Al-alloy (with no B_4C addition) since high energy discharges removed the higher amount of work material from the surface crater. Moreover, the



(a) (b) (c)

Figure 1. The microstructure images: (a) RP = 0%, (b) RP=5%, (c) RP = 10%.

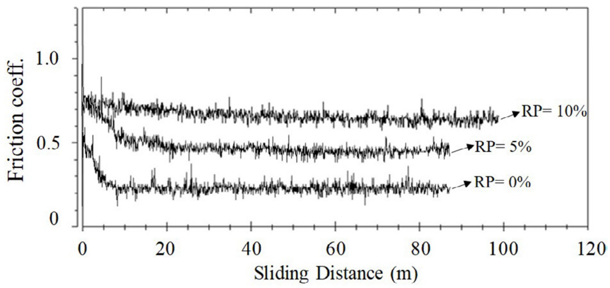


Figure 2. Friction coefficient variation throughout the tests for the sample samples.

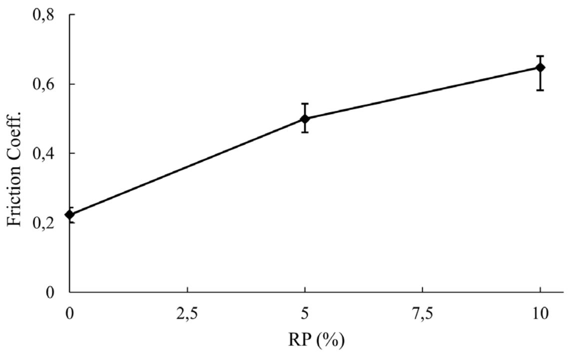


Figure 3. The friction coefficient for the samples.

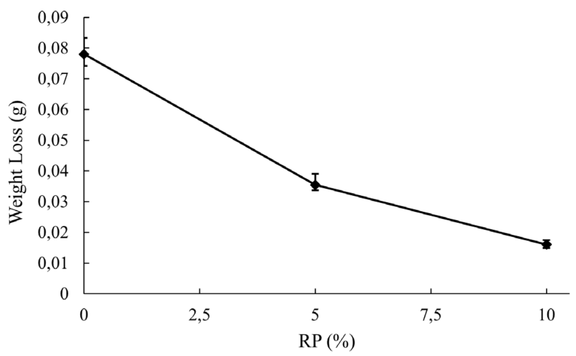


Figure 4. The measured weight loss for the samples.

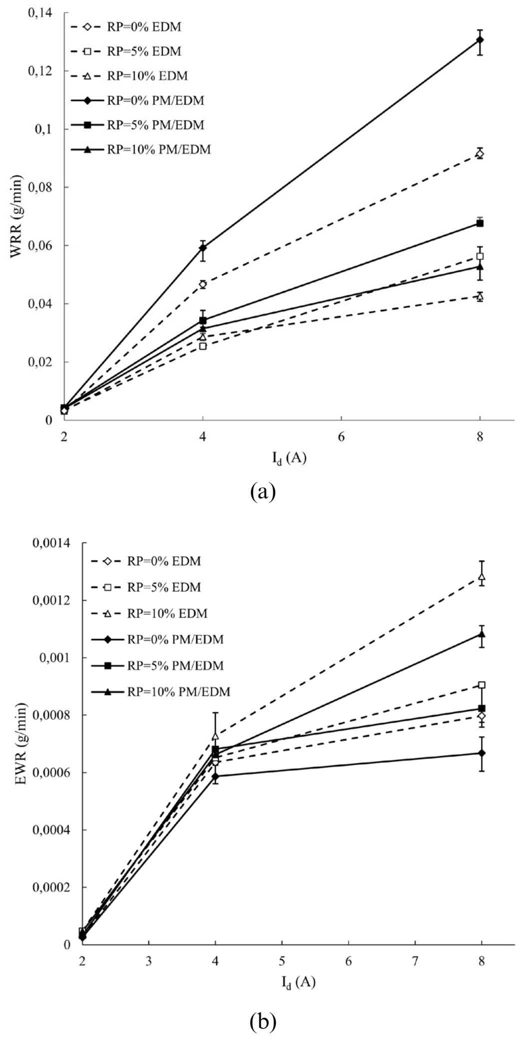


Figure 5. Effect of on a) the WRR, and b) the EWR for various RP values and machining types.

WRR was higher with a higher I_d in the same sample. Furthermore, PM/EDM had further increased WRR, which was more evident in high values. In RP=5% experiments, the WRR was lower than RP=0%. In these experiments, WRR also increased as increased. An unstable machining regime was rarely observed, possibly due to the MMC's low amount of B_4C particles. The frequency of unstable machining regimes was low compared to RP=10% experiments. The RP=10% samples had the lowest WRR among the samples. The high amount of B_4C in the sample had often resulted in undesirable arc pulse formations evident from visible burning spots (black color) on the surface and unstable machining, especially at =8 A setting.

EWR values increased as RP and increased (Fig. 5b). Although the B_4C powders in the samples were more resistant to high-temperature discharge plasma than the Al2014 matrix, they can't significantly reduce the melting and evaporation effects of the plasma channel due to being in small quantities (max RP=10%) in the samples. In other words, the presence of B_4C powder with a high melting temperature in the sample was ineffective in reducing EWR. However, because higher-density energy was discharged to the electrode and workpiece surfaces through the plasma channel at high settings, deep and large-diameter melting and evaporation craters were formed on the surfaces yielding high EWR values. The experiments showed that when PM/EDM method was used, the EWR values decreased for all RP values. The highest EWR was obtained when =8 A, RP=10%, and EDM settings were used. The lowest EWR was obtained at =2 A, RP=0% and PM/EDM settings. RP=5% samples resulted in higher EWR values than in RP=0% samples using EDM settings (Fig.

5b). High temperature in the machining gap and difficulties of removing dense machining residue from the medium caused machining instability at =8 A settings. In PM/EDM method, the machining residue's flushing was facilitated since the distribution of residues in the machining gap was over a large area. The easy cleaning of the machining medium improved the machining stability and reduced the EWR. In RP=10% samples, the EWR increased with (Fig. 5b). However, the machining with PM/EDM resulted in slightly lower EWR values. The reduction in EWR is especially pronounced with =8 A.

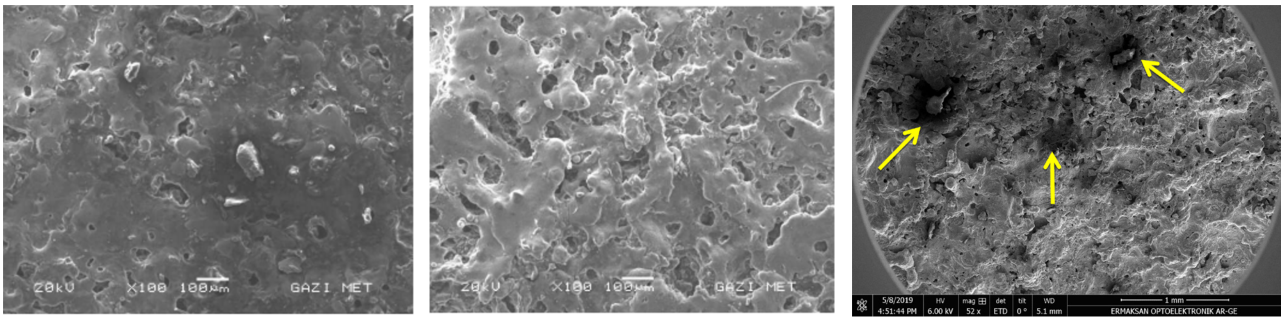
The surface images of samples machined by PM/EDM and EDM displayed resolidified surface layers formed. In Fig. 6a, a better surface finish with small surface craters was evident in machining with PM/EDM. On the other hand, larger and deeper craters were formed in machining with EDM (Fig. 6b), causing comparably inferior surface quality. The resolidified regions in composites were composed of B_4C lumps (Fig. 6c) due to high-energy discharges in all experiments with high RP and I_d values. The formed B_4C lumps (sizes about 100 µm, Fig. 6c) negatively affected the WRR and machining stabilities since the lump sizes were much larger than a typical plasma diameter, (less than 12 µm for the used machining settings in Table 3). This concludes that the plasma channel forming on the B_4C lumps would be ineffective considering the material removal.

Table 3. Results of ANOVA for WRR and EWR

Control Factor	Contribution to WRR (%)	Contribution to EWR (%)
Mach. type	1.6	2.1
I_d	73.8	89.6
RP	12.7	2.7
Error	11.97	5.3
Total	100	100

ANOVA and F-test were used to determine the relative importance of , RP and machining type (EDM and PM/EDM) to the machining performance outputs, namely MRR and EWR. The results demonstrated a low level of an experimental error (max. 11.97% and 5.3% for WRR and EWR, respectively). The ANOVA and F-test results on percentage contributions of , RP and machining type on MRR and EWR are determined as follows (Table 3):

- I_d value: Significant (73.8% and 89.6% contribution),



(a) (b) (c)

Figure 6. Samples machined at RP = 10%, = 8 A; (a) PM/EDM (b) EDM, (c) B_4C lumps.

Table 4. The WRD values obtained from the experiments and the model

Exp. Nº	Mach. type	RP (%)	I_d (A)	t_e (µm)	t_p (µm)	WRR (g/min)	P_p (W)	R_p (µm)	WRD (mm³/pulse) ×10¹⁰ Exp.	WRD (mm³/pulse) ×10¹⁰ Model	Diff. (%)
1	EDM	0	2	8	1	0.00324	46	6.86	0.173	0.32	84
2	EDM	0	4	8	1	0.04920	92	9.05	2.63	3.65	39
3	EDM	0	8	8	1	0.09140	184	12.45	4.89	6.55	34
4	EDM	5	2	8	1	0.00316	46	6.86	0.171	0.31	81
5	EDM	5	4	8	1	0.02890	92	9.05	1.56	2.03	30
6	EDM	5	8	8	1	0.05630	184	12.45	3.04	3.89	28
7	EDM	10	2	8	1	0.00311	46	6.86	0.169	0.27	59
8	EDM	10	4	8	1	0.02630	92	9.05	1.43	1.88	32
9	EDM	10	8	8	1	0.04530	184	12.45	2.46	2.92	19

- RP value: Low (12.7% and 2.7% contribution),
- Machining type: Insignificant (1.6% and 2.1% contribution).

As shown above, the parameter had the highest importance on the variation of machining performance outputs, whereas the importance of RP and machining type was low. The importance of the on the EWR, surface roughness, and power consumption was also reported by two other studies about EDM of Al/Al alloy matrix composites reinforced with B_4C particles (Kumar *et al.*, 2014; Manish and Dhakad, 2018).

All WRD values obtained from the model were higher than the experimental results. The difference is between 84% and 19% (Table 4). In fact, the differences for all cases were between 19% and 39%, except for the cases corresponding to small WRR values experienced at the low setting (at =2 A). Nevertheless, the model reflects the effects of RP on WRR correctly. The observed differences are reasonable, considering the highly complex nature of the EDM process. It can be attributed to factors such as inaccuracies of the thermal properties at elevated temperatures, the random nature of the delay time of discharge pulses, the occurrence probability of ineffective pulses and the adverse effects of excessive dielectric contamination.

4. CONCLUSIONS

- Concluding microstructural examination of the MMC samples exhibited homogenous distribution of B_4C particles with sufficient wetting between them and the Al2014 matrix material. The abrasion tests also proved homogenous B_4C particle distribution in the MMCs since the coefficient of friction remained constant throughout the tests. It was observed that the abrasion wear resistance and the friction coefficients of composites increased as the quantity of hard B_4C particles increased.
- In EDM experiments, WRR decreased with the increasing B_4C reinforcement content at constant I_d settings. The higher WRR and EWR values were obtained for each composite sample by increasing I_d values. On the contrary, without the B_4C addition, higher WRR and lower EWR values were obtained compared to composites. This was attributed to the absence of B_4C reinforcement particles destabilizing the machining regime and causing a lower removal rate. In the PM/EDM experiments, WRR values increased while EWR values decreased. Improvements in WRR and EWR were particularly more pronounced at high settings for PM/EDM experiments.
- Based on ANOVA results, was a highly effective parameter on the variations of WRR and EWR (73.7% and 89.6% contribution, respectively). In contrast, RP and machining types were much less effective.
- The model of Sarıkavak and Çoğun (2012), correctly reflected RP's effect on WRD. The differences between the WRD values of experiments and the model were attributed to the inaccuracies of thermal properties of the samples, the random nature of discharge phenomena and the existence of resolidified workpiece material on the surface craters.
- As future work, we suggest studying the surface modification, especially the surface hardening, characteristics of the B_4C-reinforced Al2014 metal matrix composite samples machined with EDM and PM/EDM, and the improvements in machining performance outputs, namely MRR, EWR and surface roughness, of the samples compacted for further densification after the vacuum infiltration process.

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