Check for updates

Original Research Article

Institution of MECHANICAL ENGINEERS
Journal of MECHANICAL ENGINEERING SCIENCE

Proc IMechE Part C:
J Mechanical Engineering Science
1–13
© IMechE 2022
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/09544062221130219
journals.sagepub.com/home/pic
SAGE

Investigation of the machinability of $B_4C + TiB_2$/Al 2024 composite manufactured by powder metallurgy with EDM

Hacı Bekir Özerkan[1], Mehmet Subaşı[2] and Muharrem Pul[3]

Abstract

In this study, the machinability of B_4C and TiB_2 reinforced Al 2024 based composites produced by powder metallurgy was investigated with EDM (Electro Discharge Machining) method using two different copper electrodes. For this purpose, composite samples were produced at 6% TiB_2 + 12% B_4C reinforcement ratios. Then, scanning electron microscopy images were taken to examine the microstructure of the composite samples. Also EDAX analyzes were performed during SEM images. In EDM machinability experiments of the composite material two different electrodes; pure copper and beryllium copper were used. The experiments were carried out using three different current (I) and arc pulse on time (t_{on}) and two different arc pulse off time (t_{off}) parameters. As a result of EDM experiments, roughness measurements of the machined surfaces were made and SEM images of the machined surfaces were taken again. According to the experimental findings, material removal rate increased in machining with CuBe tool compared to machining made with pure Cu and CuBe tools showed higher wear tendency than Cu tool sunder the same machining conditions and roughness values in CuBe electrodes were lower than machining made with pure Cu. And the roughness values of CuBe are lower than the machinings with pure Cu.

Keywords

Metal matrix composite, Al 2024, machinability, EDM, SEM

Date received: 24 June 2022; accepted: 6 September 2022

Introduction

Aluminum metal matrix composites (Al-MMC) are a class of materials that have proven successful in accomplishing of most demands of specifications in applications where lightness, high stiffness and strength are required.[1] These composites are frequently preferred in the manufacture of various industrial machine parts and automobile parts due to their favorable properties such as light weight, high strength and superior malleability combined with low density compared to iron-carbon alloys such as steel and cast iron.[2] Al 2024, which has the highest superplastic feature among Al alloys, has the highest strength with T62 heat treatment.[3] Most of the studies on aluminum alloy-based metal matrix composites are carbon and ceramic reinforced materials.[4,5] Generally the machining of composite materials is difficult due to the high abrasiveness of the reinforcing components and when processed using conventional methods, it causes damage to the workpiece and rapid wear of the cutting tool.[6] To overcome the tool damage non conventional machining techniques are employed for effective machining of MMCs.[7] Electric discharge machining (EDM) is a non-traditional erosion and material removal process with no physical contact between the tool and the workpiece.[8] Hard materials in ISO S and H classes are easily processed with EDM according to their electrical conductivity. Since there is no physical contact between the workpiece and the electrode in EDM, when voltage is applied between the electrode and the workpiece, metal-based materials can be easily shaped with the formed electric arc by ionizing the dielectric due to the high potential difference.[9] Kutlu et al.[10]

[1]Department of Mechanical Engineering, Faculty of Engineering, Gazi University, Ankara, Turkey
[2]Department of Machinery and Metal, Vocational School of Technical Sciences, Gazi University, Ankara, Turkey
[3]Department of Electricity and Energy, Kırıkkale Vocational School, Kırıkkale University, Kırıkkale, Turkey

Corresponding author:
Muharrem Pul, Department of Electricity and Energy, Kırıkkale Vocational School, Kırıkkale University, Kırıkkale, 71450, Turkey
Email: mpul@kku.edu.tr

Table 1. Properties of matrix material Al 2024 and reinforcement elements B_4C and TiB_2.

Al 2024									
Fe%	Si%	Cu%	Cr%	Mn%	Mg%	Zn%	Ti%	Other	Al%
0.5	0.5	3.8–4.9	0.1	0.3–0.9	1.2–1.8	0.25	0.15	0.15	Bal.
Density		Melting point		Hardness		Thermal conduct.		Electrical resistivity	
2.78 g/cm^3		638°C		120 HB		121 W/mK		5.82e–006 Ω.cm	
B_4C									
B%		C%		O%		Si%			
77–79		19–21		0.1		0.1			
Density		Melting point		Hardness		Thermal conduct.		Electrical resistivity	
2.52 g/cm3		2730°C		2700 Knoop		30 W/mK		9.8×10^{-8}Ω.cm	
TiB_2									
Ti%				B%					
68.9				31.1					
Density		Melting point		Hardness		Thermal conduct.		Electrical resistivity	
4.52 g/cm^3		2970°C		1800 Knoop		25 W/mK		15×10^{-6}Ω.cm	

investigated the machinability of zirconia matrix titanium nitride reinforced composites with EDM. They obtained material removal rate (MRR) higher than 1 mm^2/min and low surface roughness. Naik et al.[11] reported that the MRR increased with the increase in flow and table feed rate values, and that toff had no effect on the machinability of 5% and 10% B4C reinforced AA6063 composites. Dar et al.[12] investigated the machinability of 7% SiC and 3% Gr reinforced composite with LM25 matrix with EDM. They reported that the current and applied voltage had an effect of 81.77% and 17.17% on the increase in MRR. Subramaniam at al.[13] investigated the performance of different electrode materials such as tungsten, copper and brass in the processing of SiCp/Al MMC material with EDM and stated that pure copper performed better as electrode material and discharge current was the most important factor.

In this study, a different composite material, which is different from the literature, reinforced together with B_4C and TiB_2 and thought to be suitable for the aerospace industry, was produced. It is aimed to investigate the machinability of this composite produced by powder metallurgy with EDM. Two different electrodes, electrolytic Cu and CuBe, were used in the experiments. Three different currents (6, 15, 25 A) and arc duration (48, 99, 150 μs) and two different arc gap times (48.99 μs) were applied to compare the performance of the electrodes. Using this experimental design, the effects of electrode type, I, t_{on}, and t_{off} on MRR, tool wear rate (TWR) and surface roughness (Ra) were revealed.

Experimental procedures

Materials

For generating new mataerial Al 2024 alloy with a grain size of 149 μm was used as the matrix material. The reinforcement elements used in the test samples are B_4C powders with a grain size of 63 μm and TiB_2 powders with a grain size of 37 μm. The properties of the matrix material (Al 2024) and reinforcement elements (B_4C, TiB_2) are given in Table 1.

Fabrication of composite

Powder metallurgy technique was used in the production of composite samples. In the first stage, a homogeneous structure was obtained by mixing Al 2024, B_4C and TiB_2 powders in a propeller mixer at 500 rpm for 45 min. The weight-volume ratios of the composite mixtures used in the experiments were calculated according to the below Equation 1.

$$V_f = \frac{M_P/P_P}{\frac{M_m}{P_m} + \frac{M_P}{P_P}} \quad (1)$$

Here; V_f = Particle volume ratio, M_P = Particle weight (g), P_P = Particle density (g/cm^3), M_m = Matrix weight (g), P_m = Matrix density (g/cm^3). In the second stage, samples (ϕ35 mm) with 15 mm in thickness were prepared from the composite powder mixture by the cold pressing method under 700 MPa pressure. And lastly, the production process was completed by sintering the composite samples at 560°C for 120 minutes. EDM machinability tests were performed using a Furkan 50A ZNC-1 brand EDM machine. A full factorial experimental design was used (Table 2). Three different currents (6, 15, 25 A), three different t_{on} (48, 99, 150 μs), and two different t_{off} (99, 150 μs) were used.

EDM experiments were carried out with two different tools (electrodes), e-Cu and CuBe.The dimensions of the specimen and tool (electrode) used in the study are $12 \times 14 \times 50$ mm and $5 \times 8 \times 30$ mm, respectively. The *MarSurf PS1* brand portable roughness device was used for the roughness measurements of the test samples. The average roughness value was

Table 2. Experiment parameters for EDM machining.

Experiment number	Machining current I (A)	Power level	Pulse on time t_{on}(μs)	Pulse off time t_{off} (μs)
1	6	6	48	99
2	6	6	48	150
3	6	6	99	99
4	6	6	99	150
5	6	6	150	99
6	6	6	150	150
7	15	10	48	99
8	15	10	48	150
9	15	10	99	99
10	15	10	99	150
11	15	10	150	99
12	15	10	150	150
13	25	13	48	99
14	25	13	48	150
15	25	13	99	99
16	25	13	99	150
17	25	13	150	99
18	25	13	150	150

determined using data from various regions of the samples.

Results and discussion

Microstructure evaluation

Optical microscope images of the Al 2024 composite with 12% B_4C + 6% TiB_2 reinforcement produced by powder metallurgy that sintered at 560°C and also pure Al 2024 samples without reinforcement in Figure 1.

The structural difference between the microstructures of the pure Al 2024 sample and the B_4C + TiB_2 reinforced composite samples is clearly visible when looking at the images in Figure 1. There is a minor amount of porosity visible, in the microstructure of the pure Al 2024 sample. When comparing the pure Al 2024 sample with the reinforced composite sample, it is obvious that the pure Al 2024 sample has a porosity microstructure. However, by increasing the sintering parameters (560°C temperature and 120 min) the porosities in the microstructure may be eliminated and the interfacial lines between the grains can be reduced or even removed completely. When looking at the sample image of the B_4C + TiB_2 reinforced composite, it's clear that B_4C particles are located in the structure in a darker color. It is seen that B_4C particles in the composite structure have different sizes and sharp corners, whereas generally Al 2024 particles are in different sizes with spherical form. It can be said that TiB_2 particles are much smaller in size but have a non-sharp corner structure. TiB_2 particles are more difficult to identify in the Al 2024 matrix because they are smaller and seem brighter. When examining the optical microscope image, both B_4C and TiB_2 reinforcement particles appear to have a random distribution. In some regions, reinforcement agglomerations and porous regions can be seen. Porosity and reinforcing agglomeration are frequently encountered in such particle-reinforced metallic composites. And also, it can be considered that some B_4C particles which are larger than TiB_2 particles break away from the structure and cause the formation of porous regions within the structure.[14] In order to examine the microstructures of the samples in more detail, SEM images taken from the fractured surfaces and shown in Figure 2. In addition, elemental EDAX analyses were also carried out to determine the matrix and reinforcement elements that make up the composite structure.

When Figure 2(a) is examined, it is seen that the Al 2024 alloy powders are generally spherical in shape but there is a size difference between the Al powders. EDAX analysis result given on the side shows that the structure was formed with aluminum. The SEM image in Figure 2(b) the reinforcement element B_4C and TiB_2 phases are encountered. Since B4C is less dense than aluminum, it appears darker in the

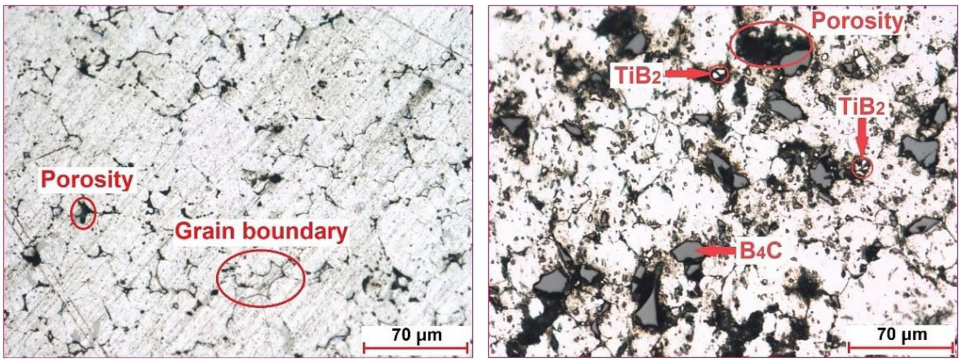

Figure 1. Microstructures of samples: (a) pure Al 2024 and (b) 12% B_4C + 6% TiB_2 reinforced Al 2024.

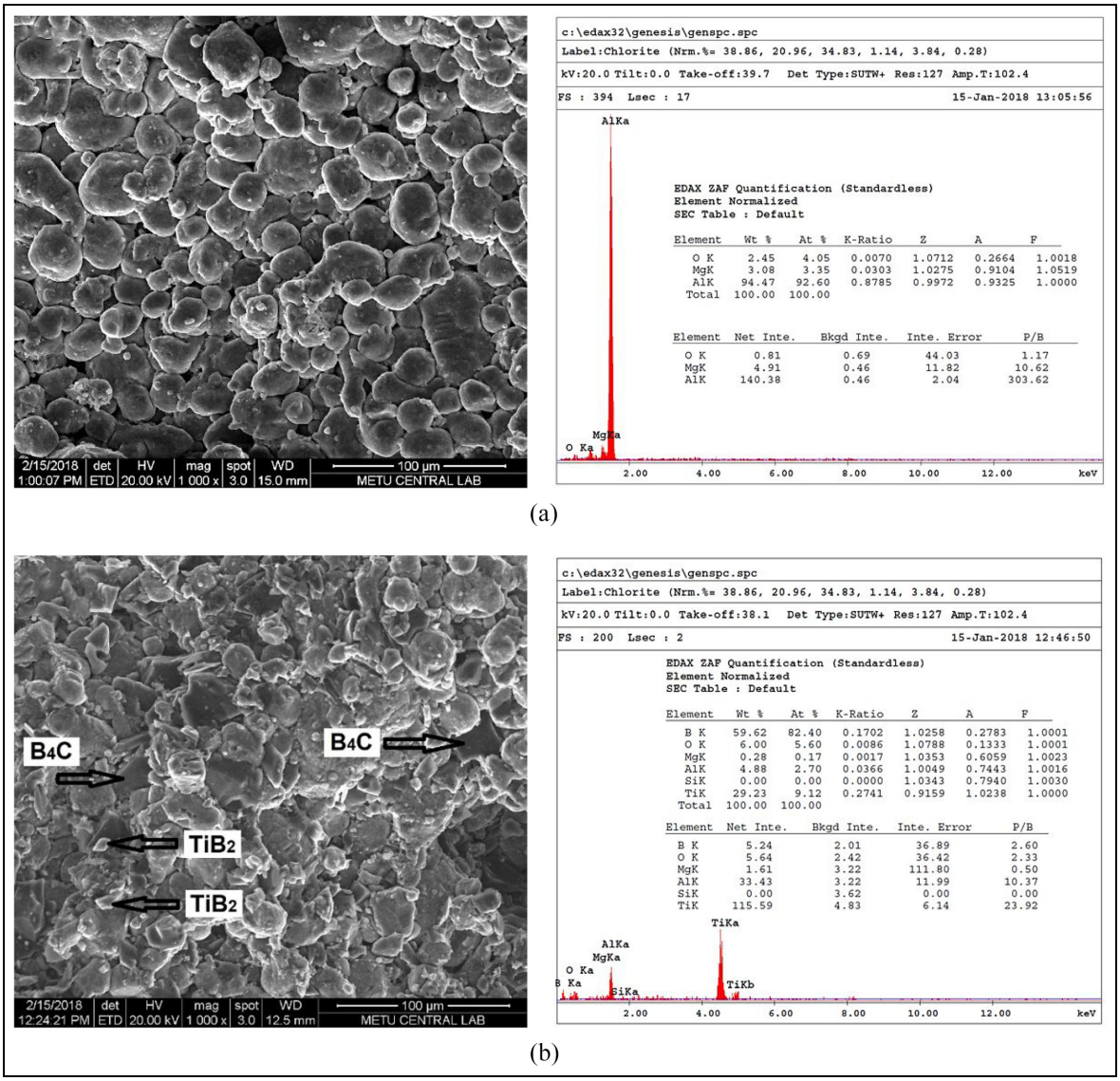

Figure 2. Fractured surface images and EDAX analyzes of test samples produced by powder metallurgy method: (a) pure Al 2024 matrix material and (b) Al 2024/B_4C + TiB_2 composite.

aluminum matrix on SEM images. TiB2, on the other hand, is more dense than aluminum and appears brighter in color than the aluminum matrix in SEM images. In the EDAX analysis on the right, the presence of the reinforcement elements in the composite structure is determined elementally.

Machinability evaluation of EDM

In this study, the machinability of the fabricated B_4C + TiB_2/Al 2024 MMC with EDM was investigated and processing performance outputs such as MRR, TWR and Ra were evaluated. Figures (3, 4, and 6) depict variation in processing performance outputs.

Current values were preferred at low, medium and high values in order to determine the ideal machining value of the material with CuBe electrodes. MRR increased at 15A current and 48 and 99 µs pulse times, but tended to decrease at 25A current and same pulse times (Figure 3(a) and (b)). This shows that other processing parameters are also effective depending on the discharge current value. The highest MRR values were determined at the same I values at 99 µs pulse times. In order to process the material very quickly, increasing the discharge current and pulse time in EDM is the most preferred parameter selection. However, as a result of the experiments, the lowest processing rates were determined at t_{on} value of 150 µs. While power level and t_{off} are constant, if arc duration is increased, MRR increases up to a certain value. It is consistent with results in the literature[15,16] and when t_{on} is increased above this value, the MRR starts to decrease. If arc duration is increased above the optimum value, discharge energy will not break the chips[17] and cause unnecessary heating of the

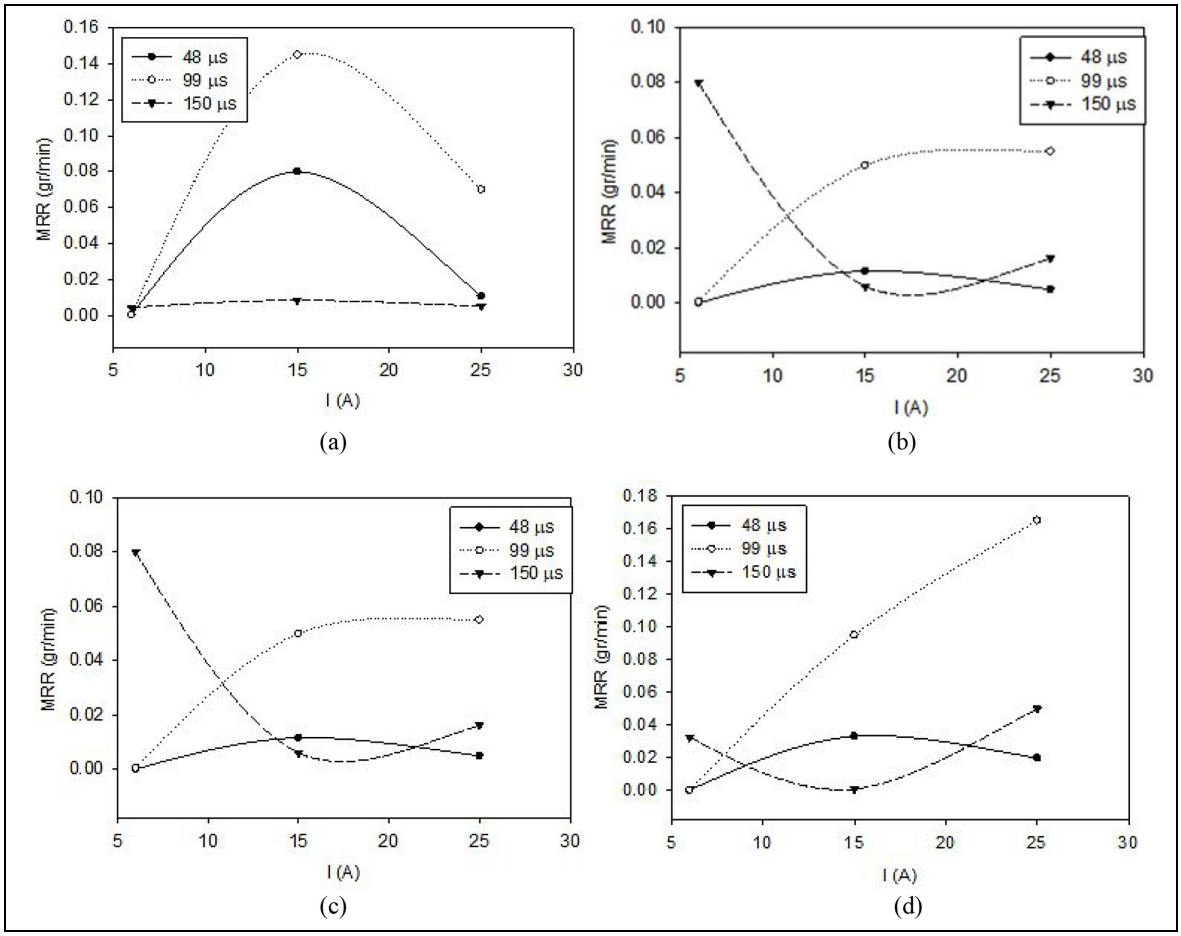

Figure 3. Variation of MRR-I-t_{on}: (a) t_{off} = 99µs constant-CuBe tool; (b) t_{off} = 150µs constant-CuBe tool; (c) t_{off} = 99µs constant-Cu tool; (d) t_{off} = 150 µs constant-Cu tool.

surface and dielectric liquid. In this study, lowest MRR values were obtained in the processings with 150 µs t_{on} value, where the t_{off} was kept constant. Because choosing this time high means an increase in the time that no sawdust is removed; the machining speed or in other words the metal removal rate (mm^3/min) is reduced.

In Figures 3(a) and 3(b), similar changes are seen at 90 and 150 µs t_{off} values, with MRR increasing at 48 and 99 µs t_{on} values and by the increase of the t_{on} value with the current, more material is eroded per unit time. It can be concluded that, MRR is generally found to be higher in processes with t_{off} = 150 µs. This situation with the increment of t_{off} value, the processing area is cleaned more effectively and the discharge energy is transmitted to workpiece with less loss in time.

The highest MRR was obtained at 6 A and 150 µs values in machinings performed with e-Cu tool by keeping the t_{off} = 99 µs value constant (Figure 3(c)). This is an unusual situation and estimated to be due to increase in conductivity due to the lack of reinforcement ceramic structures in this region of the produced material. Generally, the MRR is higher for machining with 48 and 99 µs t_{off} values. The non-homogeneous distribution of ceramic particles in the produced samples; spark discharges did not occur from time to time due to the decrease in conductivity (due to the absence of ionization in the dielectric liquid).

TWR increased in all machinings with increment of discharge current in machinings with CuBe tool. When Figure 4 is examined, the lowest TWR values were obtained in the processes with t_{on} = 150µs (Figure 4(a) and (b)). The wear increased with the decrease of the t_{on} time, and the highest tool wear was detected in machining performed at 48 µs t_{on} time. Therefore, keeping discharge duration small while the power level is high has increased the electrode wear since more sparks will be discharged from the spark discharge surface of the electrode per unit time. This is in accordance with the physical processing logic of EDM.[18]

TWR increased with increasing current value at 48µs and 99µs impact times, but TWR can be negligible in machining with t_{on} = 150 µs in both machinings with Cu and CuBe electrodes. This means that the spark discharge time was chosen unnecessarily long. In other words, it takes a long time for spark to complete the melting process in the region where it falls.

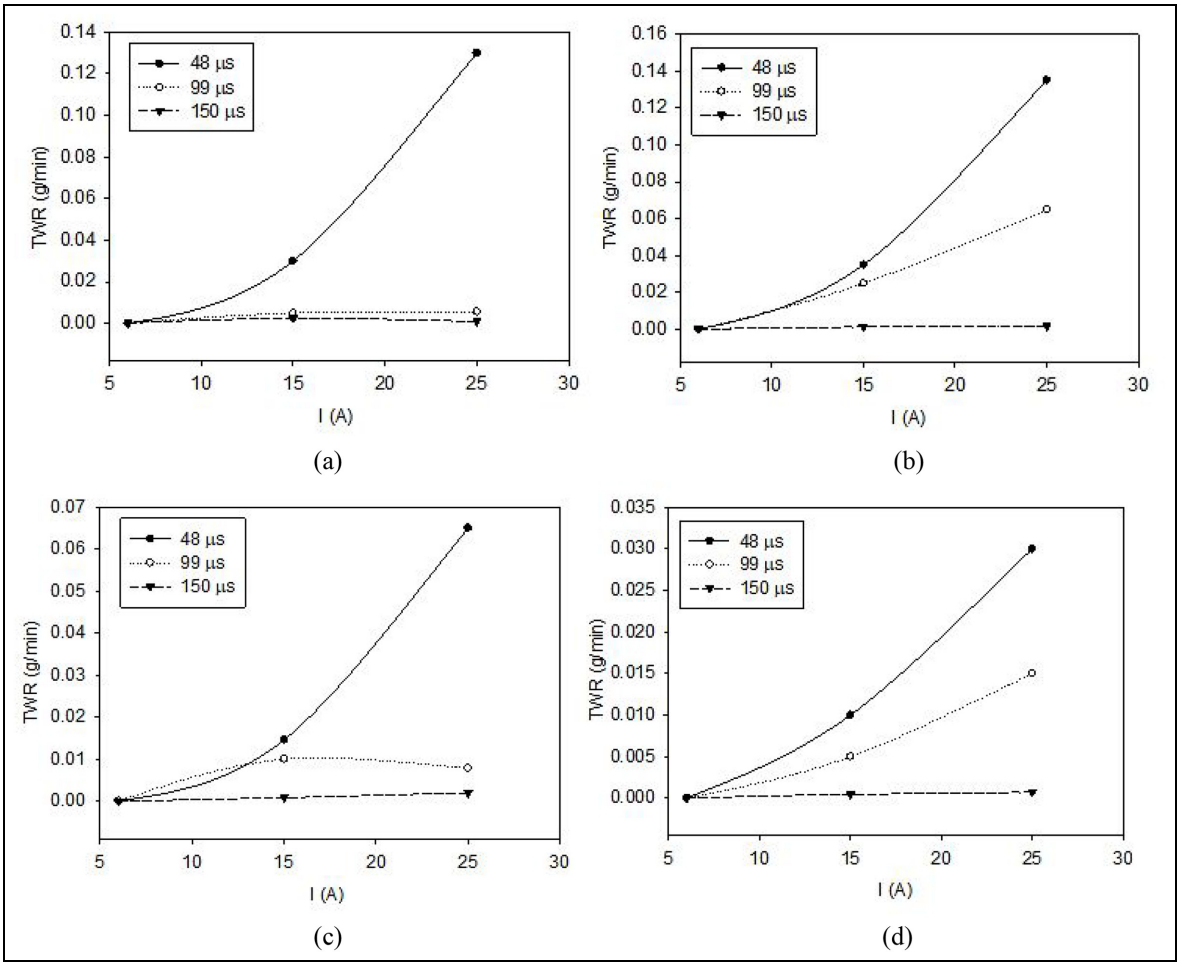

Figure 4. Variation of TWR-I-t_{on}: (a) t_{off} = 99µs constant-CuBe tool; (b) t_{off} = 150µs constant) CuBe tool; (c) t_{off} = 99µs constant-Cu tool; (d) t_{off} = 150µs constant-Cu tool.

Thus, the workpiece and the dielectric fluid are heated unnecessarily by the long-term discharge channel temperature and the material erosion rate is reduced. The number of repetitions for new spark discharge is reduced in order to reach the desired depth. Tool wear generally occurred at higher values in machining with pure copper at t_{off} = 99 µs values. With the shortening of this period, abrasive operating regime has occurred, since many consecutive spark discharges occur.

Especially when t_{on} and t_{off} are at the same value (t_{on} = 99 µs; t_{off} = 150 µs), the eroded particles adhered to the lower surface of the tool and created an elevation in the cross section of the tool. So, encountered with an undesirable situation such as a bridge-shaped outgrowth (Figure 5) in the machining gap from the tool to the workpiece. Thus, undesirable damage has occurred on workpiece since the same point will have been eroded in a short period of time that can be said to be continuous. This situation can be called an abnormal arc state and has a character similar to a short circuit state. The average working current increased to the highest level, but metal removal did not occur with the connection of workpiece and tool to each other in this way.

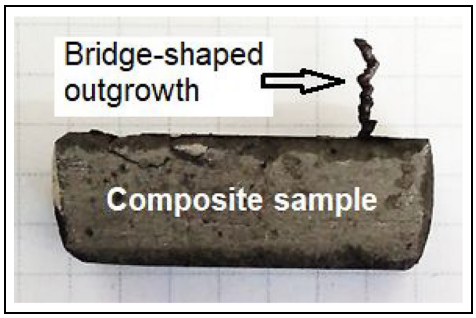

Figure 5. Bridge formed between tool (electrode) and sample.

Evaluation of surface roughness

Roughness measurements were made at five different points from machined surfaces, and the highest and lowest values were not evaluated. The *Ra* values tend

to decrease due to the increase in I and t_{on} values at constant 99 μs t_{off} values (Figure 2(b)). This situation is not encountered in processing of pure metal alloys with EDM. Due to the mechanical and thermal alloying of conductive and non-conductive materials, ceramic powders appeared as bumps on some machined surfaces. Therefore, it is thought that the ceramic particles cannot be completely removed from the surfaces at high energy discharges. *Ra* values increased with the increase of impact time in all machining made with pure Cu electrodes. Similar results have been expressed in publications in the literatre.[19] In addition, the roughness values determined at low current and high t_{on} times are higher than the machining performed at low t_{on} values. This is compatible with the EDM processing logic.[20]

In machinings performed by constant 99 μs t_{off} value, the highest *Ra* value is 150 μs t_{on} and 5.1 μs at 6A current processing level; at 25A and 48 μs t_{on} values, the lowest Ra value was measured as 2.9 μs. *Ra* decreased with increase in current at constant t_{off} = 99 μs values.

As the current increases, the discharge energy increases, resulting in an increase in the intensity of current impact forces, which leads to high erosion of the metal surface. Thus, *Ra* will increase, allowing for the formation of craters at higher depths. In Figure 13, *Ra* values increased with increase in I in machining performed at t_{off} = 150 μs at the same machining values with Cu tools. Increment of t_{on} results in a greater amount of molten metal erosion on the machined surface, as it creates a prolonged spark discharge in the spark gap. An increase in the t_{on} increases the processing time and causes an increase in *Ra* by increasing the radius of plasma channel together with spark energy.[21] In general, the surface roughness values of surfaces at 150 μs t_{on} values were found to be lower than those of 48 and 99 μs t_{on} values. On machined surfaces, there are ridges formed due to splashing of molten-solidified materials and craters due to sparks. In addition, after melting of eroded base material, some non-conductive ceramic particles are seen on the surfaces.

Similar to the *Ra* variation obtained at constant 99 μs t_{off} value with pure Cu electrodes, the *Ra* value tended to decrease with the increase of t_{on} value in the machining performed with CuBe. In machining with Cu and CuBe tools, t_{off} value of 99 μs decreased the the *Ra* value of this type of material. Normally, when t_{off} value is selected smaller than t_{on} value, burning and charring occur on the surface because spark affects the surface for a long time. However, it is considered to choose t_{off} smaller than t_{on} value for this type of mixed composite properly. An inconsistent decrease is observed in the variation of *Ra* value at 25A depending on the t_{on} value (Figure 6(c)). So can be thought that this extraordinary variation is due to the fact that reinforcement elements in the internal structure of the material are not fully eroded due to the low thermal conductivity.

When evaluated in general, the roughness values with pure Cu showed a similar trend in the machinings made with CuBe tool at the same t_{off} values. In addition, at 150 μs t_{off} time machinings with CuBe tool machining, the increasing trend of *Ra* was similar to the surfaces processed with Cu electrodes at three different t_{on} values. *Ra* values increase with the increment of the t_{off} value in the machinings made with CuBe tool (Figure 6(d)). This is in line with existing studies.[22]

The eroded particles in gap are removed more effectively with high t_{off} values, and thus there is no continuous discharge, deep melting and structural deterioration on the surfaces are reduced. As a result, surface roughness decreases in the machining performed by keeping the 99 μs t_{off} value constant. The lowest roughness value was determined as 2.1 μs at 6A current and 48 μs pulse time in the machining performed with CuBe at 150 μs t_{off} value. In general, the *Ra* values formed in machining performed under the same conditions with the pure CuBe electrode are lower than the Ra values obtained with Cu.

Evaluation of surface morphology

SEM and topographic images of surfaces belonging to all EDM machining parameters have been taken for the purpose of evaluation of surface morphology. Images at which highest and lowest roughness values have been obtained at three different current values have been given at Figures 7 for Cu electrode and at Figure 9 for CuBe electrode to be able to make a clearer evaluation.

When Figure 7 have been analyzed, it is understood that SEM and topographic images at (a), (b), (e), (f), (i), and (j) belong to surfaces arising low roughness values, on the other hand SEM and topographic images at (c), (d), g), (h), (k), and (l) belong to surfaces arising high roughness values. It is expected to increase surface damages formed together with the increase in discharge current at EDM machining operations. Increase in the current intensity leads to more energy discharge to the surface of the workpiece and hence more machining is made. When SEM images at Figure 7 have been looked at, it is seen that deformation increased at machined surfaces with the increase of rated discharge current from 6A to 25A. This deformation appears with both particle fracture and melt image of material (Figure 7(c)).[23] Besides, good surfaces and craters in terms of elevation have been formed at machined surfaces by means of melt material repelled via dielectric liquid pressure. This surface structure enhances roughness values (Figure 7(d)). There are studies emphasizing the similar results in literature.[24,25] B_4C and TiB_2 reinforced particles within the composite structure

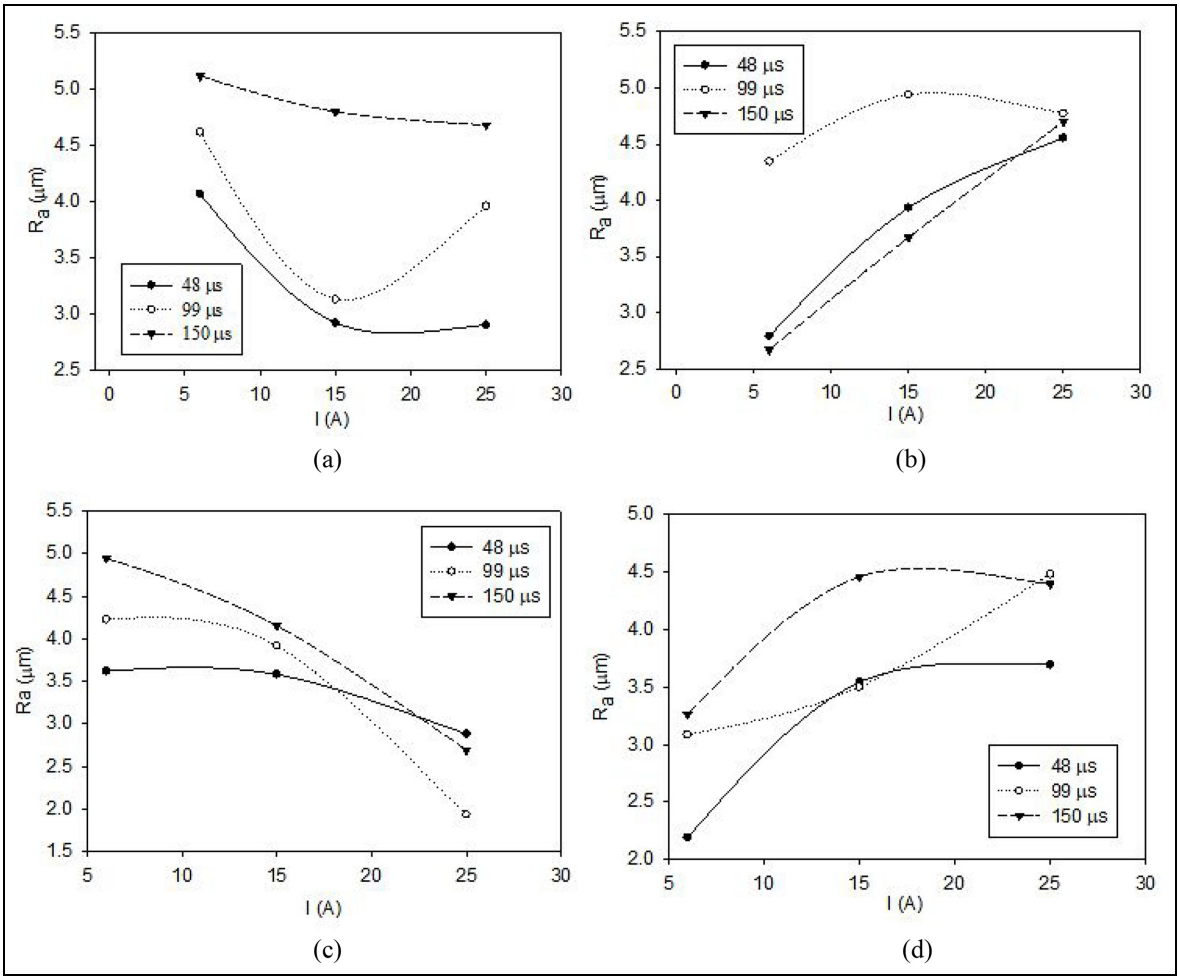

Figure 6. Variation of *Ra*-I-t_{on}: (a) t_{off} = 99 µs constant- Cu tool; (b) t_{off} = 150 µs constant-Cu tool; (c) t_{off} = 99 µs constant-CuBe tool; (d) t_{off} = 150 µs constant-CuBe tool.

may also be broken during machining and are able to form a porous area. Especially, fractures occurred densely at areas at which reinforcement agglomeration took place and measurement values which are partly unstable and uncommon have been encountered during roughness measurements. At eighteen machining processes conducted via Cu electrode, the highest MMR ratio has been obtained at sixteen numbered experiment whose test conditions are I = 25A, t_{on} = 99µs, t_{off} = 150 µs. It is expected to be obtained the highest roughness value at this experiment. However, the highest roughness value occurred at the surface obtained from five numbered experiment whose test conditions are I = 6A, t_{on} = 150 µs, t_{off} = 99 µs. It is considered that reinforcement aggregation within this composite structure and extreme porous structure formed at these areas caused this unstable situation. Agglomerated reinforcement elements and porosities formed by them by leaving structure during machining have been seen at Figure 8. Besides, Al 2024 matrix material layers melting highly and hardening again are available at large portions of machined surfaces (Figure 8(c)).

Another surface damage encountered in machining this kind of particle reinforced composites is crack formation. In case that there is an important difference between thermal properties of metal matrix forming composite structure and ceramic reinforcement element, different behaviors shown by materials during machining via EDM may cause the formation of cracks on machined surfaces. It is also expressed in the literature that this kind of composites are more sensitive to crack formation in machining via EDM method.[26,27] It is understood that respectively rated current and pulse duration are important factors on surface roughness. Similar results have been presented in literature.[28,29]

When Figure 9 have been examined, surface structures which are similar to images at Figures 9 belonging to Cu electrode have been met. Difference has been seen clearly when topographic images belonging to surfaces obtained lowest and highest roughnesses at machinings for three different discharge currents have been investigated (b), (d), (f), (h), (j), and (l) images in Figure 9. The surface appearance where the lowest surface roughness was measured as 1.93 µm in

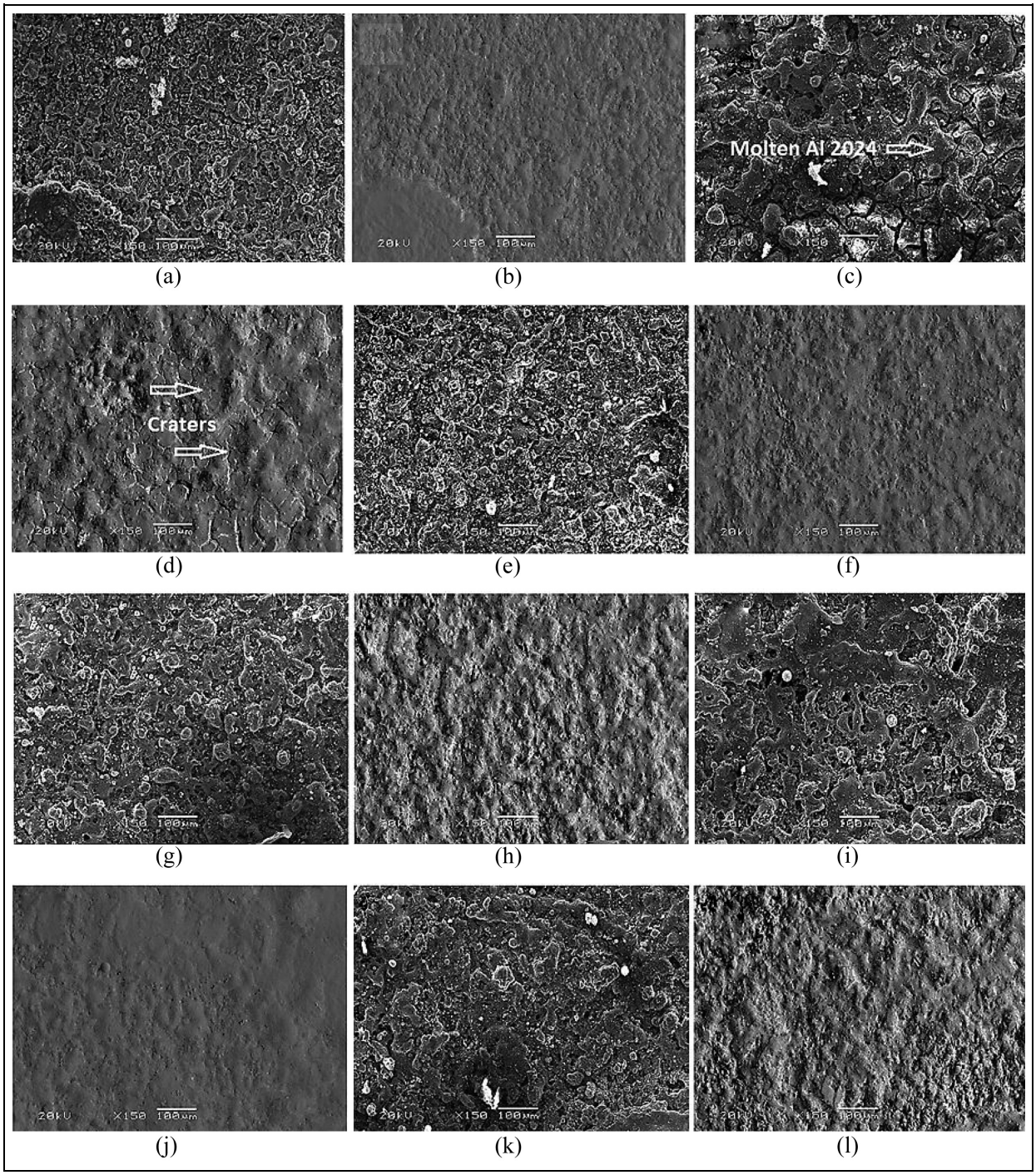

Figure 7. SEM and Topographic images of surfaces machined via **Cu** electrode, (a) and (b) $I = 6A$, $t_{on} = 150\mu s$, $t_{off} = 150\ \mu s$ (lowest roughness), (c) and (d) $I = 6A$, $t_{on} = 150\ \mu s$, $t_{off} = 99\ \mu s$ (highest roughness), (e) and (f) $I = 15A$, $t_{on} = 48\ \mu s$, $t_{off} = 99\ \mu s$ (lowest roughness), (g) and (h) $I = 15A$, $t_{on} = 99\ \mu s$, $t_{off} = 150\ \mu s$ (highest roughness), i) and j) $I = 25A$, $t_{on} = 48\ \mu s$, $t_{off} = 99\ \mu s$ (lowest roughness), (k) and (l) $I = 25A$, $t_{on} = 99\ \mu s$, $t_{off} = 150\ \mu s$ (highest roughness).

the experiments with CuBe electrode is shown in Figure 9(b) ($I = 25A$, $t_{on} = 99\ \mu s$, $t_{off} = 99\ \mu s$). Highest surface roughness has been seen in the topographic image given in Figure 9(c). Machining parameters which are $I = 25A$, $t_{on} = 150\ \mu s$, $t_{off} = 150\ \mu s$ have been applied in this EDM process. According to these results, it may be stated that Al 2024 which is matrix material spreads to the surface by melting more together with the increase of I and decreases roughness value. However, lowest roughness value has been achieved at machining conducted at not 6A of rated current, but 15A of rated current. Even if rated current and MRR are the most important parameters on surface roughness, unstable results have been encountered due to structure of this kind of particle reinforced composites. It is considered that

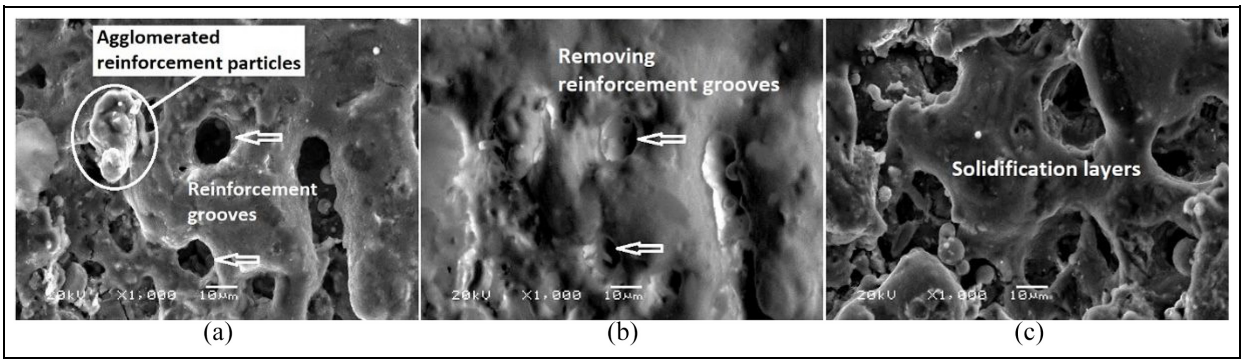

Figure 8. Reinforcement element porosities on the surface and Al 2024 which hardened again after melting.

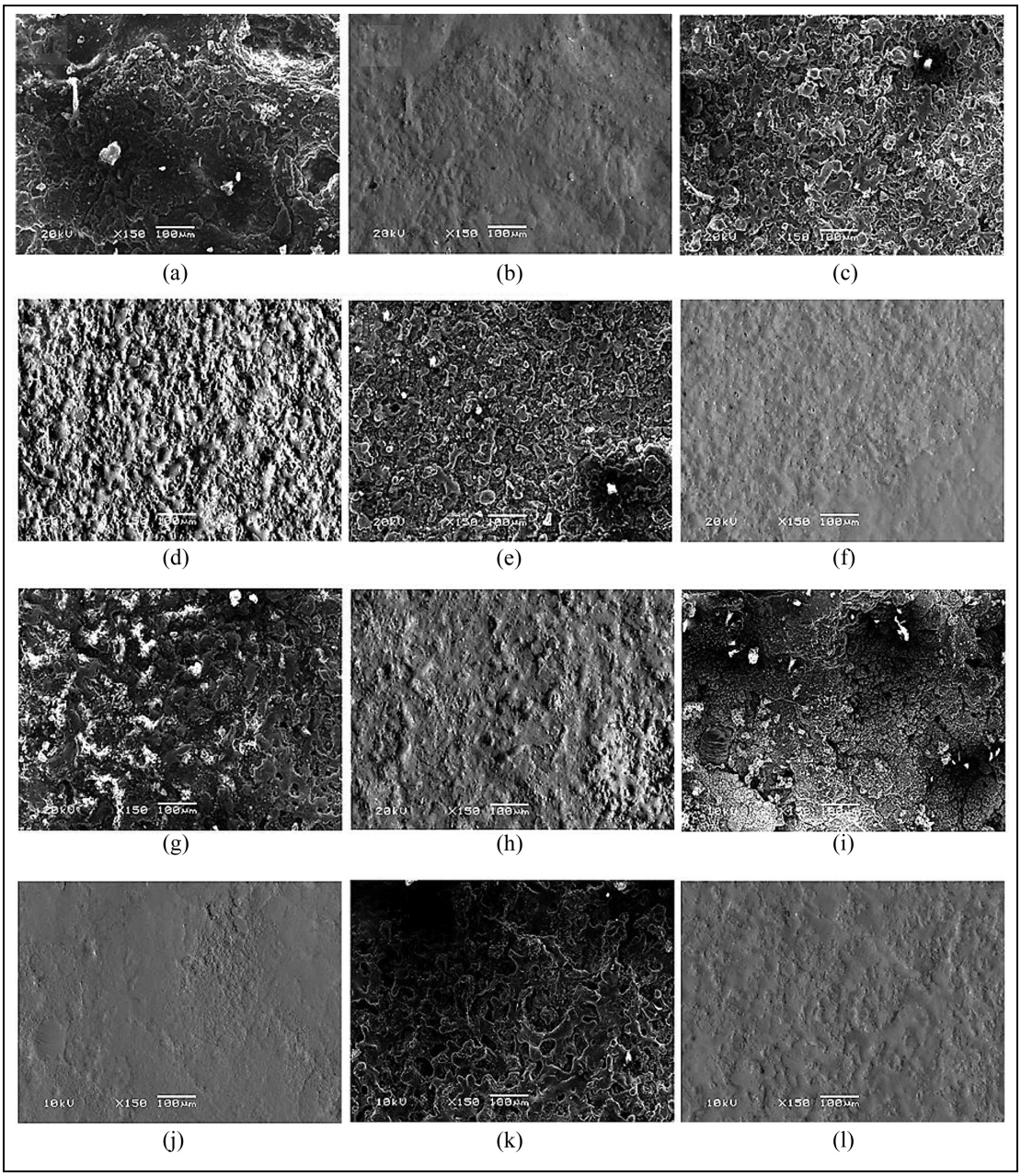

Figure 9. SEM and Topographic images of surfaces machined via **CuBe** electrode, (a) and (b) $I = 6A$, $t_{on} = 150$ µs, $t_{off} = 150$ µs (lowest roughness), (c) and (d) I = 6A, $t_{on} = 99$ µs, $t_{off} = 99$ µs (highest roughness), (e) and (f) $I = 15A$, $t_{on} = 150$ µs, $t_{off} = 150$ µs (lowest roughness), (g) and (h) $I = 15A$, $t_{on} = 99$ µs, $t_{off} = 99$ µs (highest roughness), (i) and (j) $I = 25A$, $t_{on} = 99$µs, $t_{off} = 99$ µs (lowest roughness), (k) and (l) $I = 25A$, $t_{on} = 150$ µs, $t_{off} = 150$ µs (highest roughness).

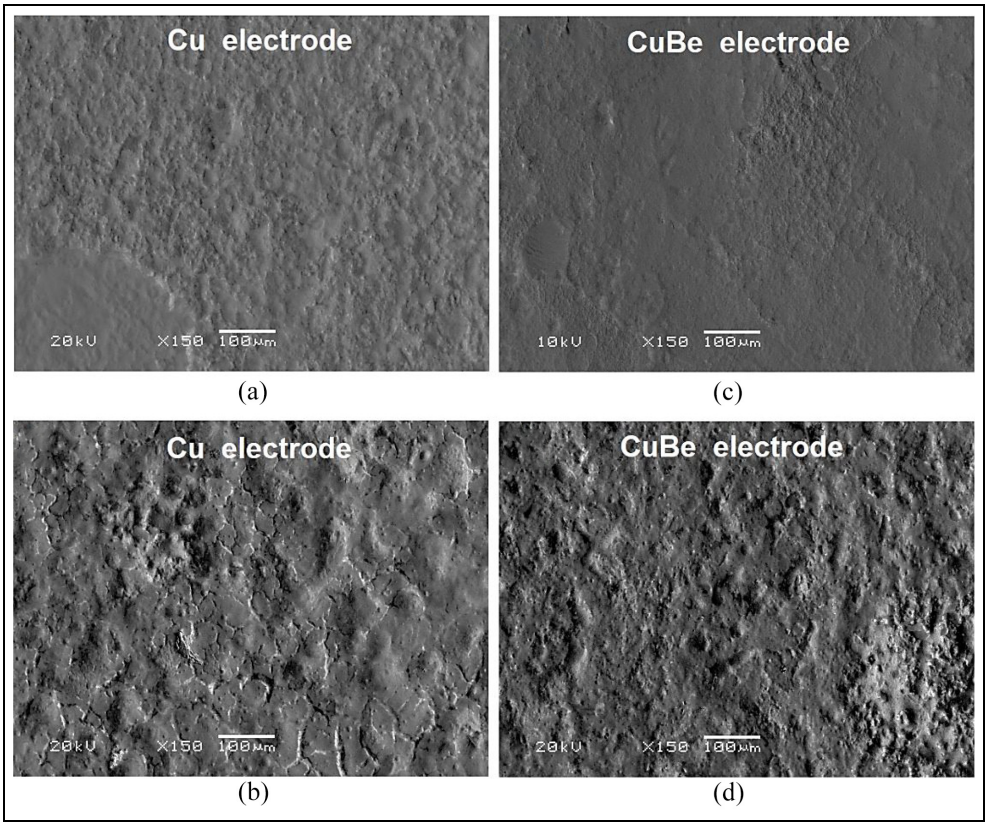

Figure 10. Surface images of composites machined via Cu and CuBe electrodes, (a) and (c) surfaces having lowest roughness, (b) and (d) surfaces having highest roughness.

random distribution of B_4C ve TiB_2 reinforced particles within composite structure and reinforcement agglomeration that happened regionally caused unexpected material behaviors during machining.[30] The very different thermal properties of aluminum and reinforcement elements led to extraordinary roughness values.

In this experimental study, machining with the same machining parameters has been made via EDM by using two different electrodes which are Cu and CuBe. In addition, these two different electrodes were compared. For this purpose, topographic images of surfaces machined via Cu and CuBe electrodes have been given side by side at Figure 10. Selected images are images at which lowest and highest roughness values have been obtained at three different rated current values.

When it was looked at topographic SEM images, it was seen that surfaces machined via CuBe electrode are less rough than surfaces machined Cu electrode. This difference seemed explicitly in Figure 10(a) and (c). When surface roughnesses in Figures 7 and 9 have been evaluated collectively, it was understood that roughness amounts of surfaces machined via CuBe electrode are a little less compared to surfaces machined via Cu electrode. When it was evaluated in general, conclusions were drawn that the difference between Cu and CuBe electrodes used in experiments is not too much and usage of CuBe electrode is proper at EDM machining of these kinds of composites.

Conclusion

In this study, EDM machining performance outputs MRR, TWR and Ra of $B_4C + TiB_2$/Al 2024 MMC produced by powder metallurgy were investigated by using e-Cu and copper-beryllium (CuBe) electrode materials.

- The MRR increased up to 99 µs t_{on} with increasing current, but decreased at 150 µs pulse on time in machining with CuBe electrodes. It can be said that t_{on} value of 99 µs was the threshold for the increase of MRR. In general, the MRR in machining with CuBe tool increased compared to the values obtained with pure Cu.
- TWR has decreased with the increase of the pulse duration, and the wear rate of 150 µs t_{on} is negligible despite the increase in current. When evaluated in general, CuBe tools showed a higher wear tendency than Cu tools under the same machining conditions.
- In the machining performed at the same t_{on} and t_{off} values, an undesirable situation such as a

bridge-like overgrowth was occured due to the adhesion of the eroded particles towards the workpiece at the tool tip.
- With the increase of current and pulse time, *Ra* values tended to decrease in machining with 99 μs t_{off} value. In processing with 150 μs t_{off} time, the roughness values of the machined surfaces decreased with the increase in I and t_{on}. The roughness values of CuBe electrodes are lower than the machinings with pure Cu.
- It has been determined that the rated current and the impact time are the most important factors on the surface roughness respectively.
- It has been understood that the uneven distribution and agglomeration of the reinforcing element B_4C and TiB_2 particles in the composite structure have a negative effect on the surface roughness and sometimes cause unstable values to be obtained.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Muharrem Pul https://orcid.org/0000-0002-0629-3516

References

1. Nturanabo F, Masu L and Kirabira JB. *Novel applications of aluminium metal matrix composites, aluminum alloys and composites*. London: Intech Open Ltd., 2019, pp.15–55.
2. Şenel MC and Gürbüz M. Synergistic effect of graphene/boron nitride binary nanoparticles on aluminum hybrid composite properties. *Adv Compos Hybrid Mater* 2021; 4: 1248–1260.
3. Wang G. Superplastic forming (SPF) of complex sheet metal parts and structures. In: *Encyclopedia of materials: metals and alloys*, vol. 4. Elsevier, 2022, pp.417–434.
4. Pul M. Effect of sintering on mechanical property of SiC/B4C reinforced aluminum. *Mater Res* 2018; 6: 016541.
5. Umasankar V, Anthony Xavior M and Karthikeyan S. Experimental evaluation of the influence of processing parameters on the mechanical properties of SiC particle reinforced AA6061 aluminium alloy matrix composite by powder processing. *J Alloys Compd* 2014; 582: 380–386.
6. Teti R. Machining of composite materials. *CIRP Annals* 2002; 51(2): 611–634.
7. Marigoudar RN and Sadashivappa K. Effect of machining parameters on MRR and surface roughness in machining of ZA43/SiCp composite by WEDM. *Int J Appl Sci Eng* 2013; 11: 317–330.
8. Paswan K, Pramanik A, Chattopadhyaya S, et al. A novel approach towards sustainable electrical discharge machining of metal matrix composites (MMCs). *Int J Adv Manuf Technol* 2020; 106(3): 1477–1486.
9. Urtekin L, Özerkan HB, Cogun C, et al. Experimental ınvestigation on wire electric discharge machining of biodegradable AZ91 Mg alloy. *J Mater Eng Perform* 2021; 30: 7752–7761.
10. Kutlu A, Gommeringer A and Kern F. Mechanical properties and electrical discharge machinability of SPS sintered Y-TZP-and YGd-TZP-titanium nitride composites. *Open Ceramics* 2021; 6: 100093.
11. Naik TP, Gairola S, Patowari PK, et al. Wire electrical discharge machining of AA6063/B4C composite fabricated by stir-casting process. *Mater Today* 2021; 46(20): 10845–10853.
12. Dar SA, Kumar J, Sharma S, et al. Investigations on the effect of electrical discharge machining process parameters on the machining behavior of aluminium matrix composites. *Mater Today* 2022; 48(5): 1048–1054.
13. Subramaniam V, Baskar N and Sathiya Narayanan C. Optimization of electrical discharge machining parameters using artificial neural network with different electrodes. In: *5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014)*, IIT Guwahati, Assam, India, 12–14 December 2014.
14. Pul M. The effect on mechanical properties of reinforcement amount at B4C + TiB2 reinforced Al 2024 based composites produced by powder metallurgy. *Int J Eng Res Dev* 2019; 11(1): 87–99.
15. Özerkan HB. Simultaneous machining and surface alloying of AISI 1040 steel by electrical discharge machining with boron oxide powders. *J Mech Sci Technol* 2018; 32(9): 4357–4364.
16. Yusron RM, Purnomo DA, Arif S, et al. Micro topography on tool steel processed using wire electrical discharge machining. In: *CESIT 2020 international conference on culture heritage, education, sustainable tourism, and innovation technologies*, Medan, Indonesia, 17–18 September 2020, pp.165–172.
17. Erdem O, Çoğun C, Ürtekin L, et al. The effect of powder mixed and heated dielectric on drilling performance of electric discharge machining (EDM). *J Fac Eng Archit Gaz* 2016; 31(3): 531–544.
18. Urtekin L, Bozkurt F, Özerkan HB, et al. Ti6Al4V alaşımının elektro erozyon ile işlemesinde elektrolitik Cu ve CuBe takım elektrotlarının performansının karşılaştırılması. *El-Cezeri* 2021; 8(3): 1455–1461.
19. Chen J-P, Gu L and He G-J. A review on conventional and nonconventional machining of SiC particle-reinforced aluminium matrix composites. *Adv Manuf* 2020; 8: 279–315.
20. Çakıroğlu R and Günay M. Comprehensive analysis of material removal rate, tool wear and surface roughness in electrical discharge turning of L2 tool steel. *J Mater Res Technol* 2020; 9(4): 7305–7317.
21. Singh M, Maharana S, Yadav A, et al. An experimental investigation on the material removal rate and surface

roughness of a hybrid aluminum metal matrix composite (Al6061/SiC/Gr). *Metals* 2021; 11: 1449.
22. Paswan K, Pramanik A, Chattopadhyaya S, et al. A novel approach towards sustainable electrical discharge machining of metal matrix composites (MMCs). *Int J Adv Manuf Technol* 2020; 106(3): 1477–1486.
23. Keskin G, Küçüktürk G, Pul M, et al. The effect of discharge current and reinforcement ratio on the microstructure and roughness of the machined surface in the machining of AA7075 matrix B4C + SiC reinforced hybrid composites by powder reinforced EDM Method. *Int J Eng Res Dev* 2021; 13(2): 489–495.
24. Suresh Kumar S, Uthayakumar M, Thirumalai Kumaran S, et al. Investigating the surface integrity of aluminium based composites machined by EDM. *Def Technol* 2019; 15: 338–343.
25. Bhuyan RK, Routara BC, Parida AK, et al. Parametric optimization of Al-SiC12% metal matrix composite machining by electrical discharge machine. In: *5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014)*, IIT Guwahati, Assam, India, 12–14 December 2014, Paper no. 345, pp.1–6.
26. Patil NG and Brahmankar PK. Some investigations into surface characteristics of wire electro-discharge machined metal matrix composites. *Int J Adv Manuf Technol* 2010; 48: 537–555.
27. Al-Amin Md, Abdul-Rani AM, Rao TVVLN, et al. Investigation of machining and modified surface features of 316L steel through novel hybrid of HA/CNT added-EDM process. *Mater Chem Phys* 2022; 276: 125320.
28. Le VT. An investigation on machined performance and recast layer properties of AISI H13 steel by powder mixed-EDM in fine-finishing process. *Mater Chem Phys* 2022; 276: 125362.
29. Prabhua M and Shanmughasundaram P. Material characterization and parametric optimization of unconventional machining of TiN and TaC reinforced stir casted vitallium metal matrix composite. *Mater Res* 2020; 23(3): e20190317.
30. Malek O, Vleugels J, Perez Y, et al. Electrical discharge machining of ZrO2 toughened WC composites. *Mater Chem Phys* 2010; 123(1): 114–120.