Sigma J Eng Nat Sci, Vol. 42, No. 6, pp. 1965−1972, December, 2024

Sigma Journal of Engineering and Natural Sciences
Web page info: https://sigma.yildiz.edu.tr
DOI: 10.14744/sigma.2024.00160

Research Article

Investigation of machinability by electrical discharge machining method of ZA27/MWCNT composites produced by powder metallurgy

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ARTICLE INFO

Article history
Received: 11 July 2023
Revised: 31 August 2023
Accepted: 04 November 2023

Keywords:
EDM; Machinability; Metal Matrix Nano Composite; MWCNT; ZA27

ABSTRACT

In recent years, nano-doped metal matrix composites have started to take place among the developed composites. In this study, powder metal undoped ZA27 alloy and 0.5% wt% multi-walled carbon nanotube (MWCNT) doped nano-composite machinability in EDM (electrical discharge machining) were researched. Microstructures of ZA27 nano-doped composites were examined under a scanning electron microscope (SEM), and their hardness measurements were made. Obtained test results were compared with that of ZA27 samples without nanodoped. In the SEM analysis, the production method applied was generally successful, and the porous regions encountered in some parts of the composite structure were due to the difficulty in homogeneously dispersing the MWCNT reinforcement material. The metal's material removal rate (MRR) increased with the addition of MWCNT powders that raised conductivity and decreased tool wear rate (TWR) compared to the pure ZA27 material.

Cite this article as: Özerkan HB, Subaşı M, Pul M. Investigation of machinability by electrical discharge machining method of ZA27/MWCNT composites produced by powder metallurgy. Sigma J Eng Nat Sci 2024;42(6):1965−1972.

INTRODUCTION

In recent years, research on metal matrix composites (MMC), which are preferred in many sectors such as medicine, defense, automotive, aerospace, energy, infrastructure, maritime, transportation, food, and sports are increasing [1,2]. In these researches, mainly aluminium and magnesium alloys constitute the majority. However, recently, the production and examination of the properties of zinc matrix ceramic reinforced composites has been a field of interest for many researchers. ZA27 coded zinc-aluminum alloy (Zamac) is widely used in the automotive industry, sports equipment, toys, hardware, decoration, white goods, etc., due to its suitability for mass production, high corrosion resistance, low melting temperature and superior workability. In addition, zinc-aluminium (ZA) alloys are known to be important bearing materials especially suitable for high-load and low speed applications. They are reported to be environmentally friendly materials with good processing

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This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkilic

Published by Yıldız Technical University Press, İstanbul, Turkey

properties and low initial cost, highlighting their excellent castability [3]. ZA27 alloy is used as the base material in the development of MMC materials and the reinforcement element is as effective as the base material in the development of the properties of composite materials. The reinforcement element carries a large part of the load on the composite. The use of nanomaterials as reinforcement elements in the production of such composites is becoming increasingly common [4]. Among these materials, materials such as nano-sized B_4C, SiC, SiO_2, Al_2O_3, MgO, TiB_2, TiC, carbon nanotubes (CNT) and nanographene (GNP) stand out in the technology. In addition to these reinforcement elements, some researchers have produced “pumice reinforced AA7075 syntactic foams as composites” and investigated their machinability by face turning [5].

In recent years, materials containing one-dimensional CNT and two-dimensional graphene have emerged as an important new class for structural engineering and functional device applications due to their exceptionally high elastic modulus and mechanical strength. Along with their aspect ratio (i.e. length-to-thickness or length-to-diameter ratio) properties, graphene and CNT are considered the most promising reinforcing fillers for the fabrication of composite materials [6]. There are many studies in the literature in which the very superior properties of carbon nanomaterials are expressed [7-9]. CNTs are the most important of all nanomaterials, and they are tubular structures with nanoscale diameter and micron size in the simplest sense. In other words, from a structural standpoint, CNTs can be imagined as hollow cylinders made of one or more sheets of graphene (a single layer of graphite) (Figure 1). The cylinder diameter may range from 0.4 nm to 100 nm or higher. The sizes of CNTs, which can vary depending on the production method and conditions, can range from hundreds of μm to cm [10]. It has been observed that CNTs have stiffness up to 1000 GPa, tensile strength of 100 GPa and thermal conductivity values up to 6000 W/mK. These studies show that CNTs are the strongest fibres known to mankind with extraordinary properties [11].

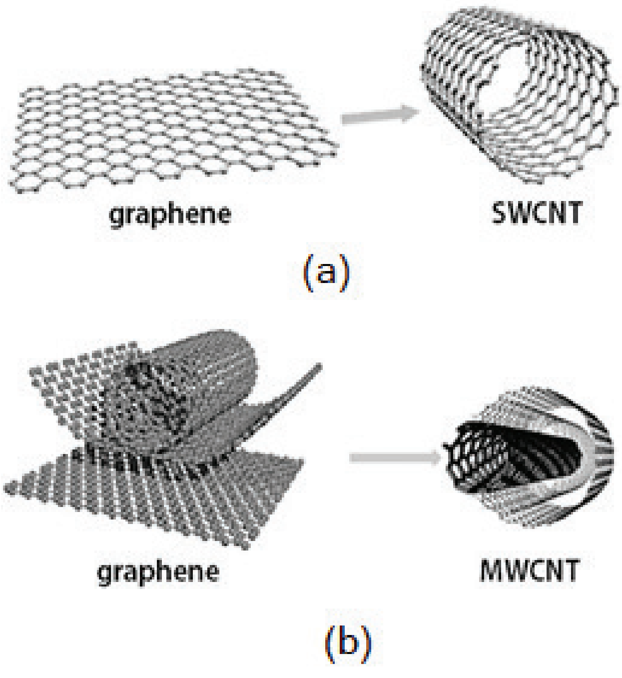

Figure 1. Formation of (a) single and (b) multi-walled carbon nanotubes from graphene nanoplate.

In studies on metal matrix composites, a large number of aluminium-based nano-composite studies have been carried out. However, it has been seen that there are not enough domestic and foreign studies on ZA27-based nanocomposites, which is a zinc-based alloy, in the literature. Metal matrix composite materials are subjected to some shaping processes depending on where they will be used. These shaping processes can be traditional chipless or machining methods, as well as some non-traditional machining methods can be applied because metal matrix composites are difficult to shape with traditional methods due to the high hardness that occurs in their structures due to the additives reinforced into them [12]. Therefore, recently, non-traditional processing methods such as EDM have been the subject of research to overcome this problem. In the literature, there are some studies on the mechanical properties and machinability of nanomaterial doped, ZA27 and different metal matrix composites [13-18].

At this point, the importance of tool conductivity was emphasised in some similar studies. In comparing the performance of CuBe and E-Cu electrodes, it was expressed that the E-Cu electrode performed better than the CuBe electrode in processing TiN-coated Ti6Al4V because of its higher conductivity [19]. However, no study has been encountered to examine the machinability of ZA27-based nano-doped composites with EDM.

In this experimental study, the machinability of ZA27 matrix MWCNT added composites produced by powder metallurgy technique, unlike the literature, was investigated by EDM method. The MMR and TWR ratios were compared with the results in machining the MWCNT-free ZA27 alloy.

MATERIALS AND METHODS

Some technical properties of the ZA27 matrix material and MWCNT reinforcement element in powder form obtained from the Nanograph Nano Technology Turkey Company are given in Table 1.

In this study, composite materials previously produced by the powder metallurgy method within the scope of Scientific Research Project numbered 2018/043 were used. Composite materials were produced by doping 0.5% by weight of MWCNT in ZA27 matrix. The powder mixture, prepared by adding 0.5% MWCNT by weight into the ZA27 matrix material, was mixed in a ball mill at 300 rpm for 2 hours and then compressed in a hydraulic press under

Table 1. ZA27 matrix and MWCNT reinforcement material specifications [20-22]

ZA 27						
Al %	**Mg %**	**Cu %**	**Fe %**	**Pb %**	**Cd %**	**Zn %**
25.5-28.0	0.01-0.02	2.0-2.5	0.075	0.006	0.006	Remain
Density, (g/cm^3)	**Melting Point, (°C)**	**Hardness, (HBW)**	**Tensile Strength, (MPa)**	**Electrical Conductivity, (S/m)**	**Thermal Conductivity, (W/mK)**	**Elongation, (%)**
5.0	376-485	105-125	421	1.72	123	3-6
MWCNT						
Purity, (%)	**Outer diameter, (nm)**	**Inner diameter, (nm)**	**Length, (µm)**	**Electrical Conductivity, (S/m)**	**Thermal Conductivity, (W/mK)**	**Specific Surface Area, (m^2/g)**
92	8-10	5-8	1-3	9800	3000	240

500 MPa pressure in a steel mold. Then, the compressed composite samples were placed in the heat treatment furnace. The temperature of the heat treatment furnace was gradually increased to 450°C in 45 minutes and the production process was completed by sintering at these temperatures for 90 minutes. Images of the composite samples whose production process was completed were taken with a scanning electron microscope (SEM) to examine their microstructures. Then, hardness measurements of composite materials were made according to the Brinell method.

Table 2. EDM experiment design parameters

Exp. No	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

In hardness measurements, a load of 15,625 kg was applied with a 2.5 mm diameter steel ball [20-22].

Machinability experiments were carried out in two stages as composite materials and pure ZA27 blank sample. EDM machinability tests were carried out using Furkan 50A ZNC-1 brand EDM machine. Experiments using the full combination experimental design presented in Table 2, like as three different currents (6, 15, 25 A), three different pulse on times (t_{on}; 48, 99, 150 µs) and two different pulse off times (t_{off}; 99, 150 µs) were used. The power level values given in Table 2 are used to set the processing current intensity. Increasing the power level without changing the arc interval/ arc duration (t_{on}/t_{off}) ratio increases the MRR (mm^3/min) due to the increase in current intensity.

RESULTS AND DISCUSSION

Microstructure

SEM images at different magnifications taken from 0.5% MWCNT added composite materials produced by powder metallurgy method are given in Figure 2.

The production parameters such as compression pressure, sintering temperature and time applied in the production of composites are other factors affecting the homogeneity of the composite structure [20]. When the SEM images (Figure 2a) are examined, it is understood that the sintering process generally provides the neck and bond formation between the ZA27 particles. However, it is also seen that partially porous (porous) regions occur within the composite structure. This structural defect, which is frequently encountered in particle-reinforced metallic composites, has been reported in the literature in different studies.

Dalmış et al. their study, it was reported that the addition of nano-graphite decreased the density values of the composites and increased the porosity ratio. It has also been

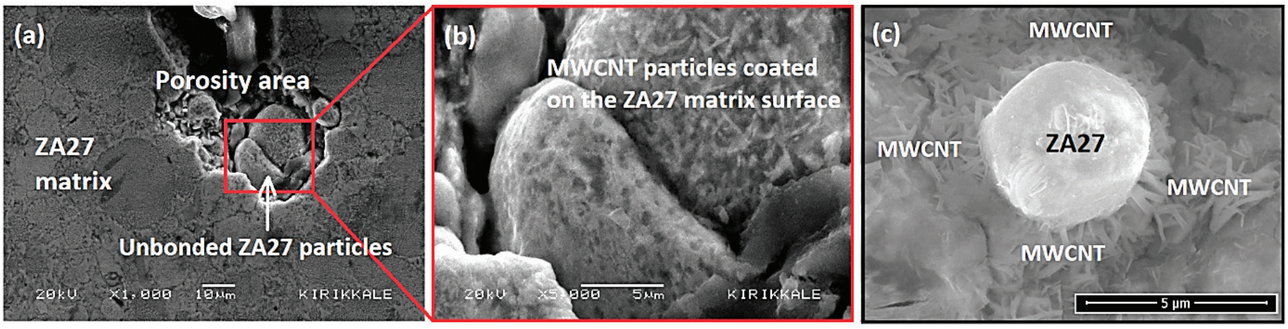

Figure 2. ZA27/MWCNT composite internal structure images.

stated that porosity is known as a common and undesirable feature of metal matrix composites produced by powder metallurgy method and that it affects the properties of the composites tremendously [23]. El-Sayed et al. their a similar study, it was stated that the mixing process of raw materials is an important first step in controlling the distribution and porosity of particles that affect the mechanical and tribological behavior of composites [24]. Saheb et al. their study, it was stated that porosity was mainly caused by CNT agglomeration [25]. Zhou et al. some other factors such as the distribution, texture, interfacial bonding and porosity of CNTs in the composites produced by the powder metallurgy method will significantly affect the strength of the composites. They also pointed out other factors in their studies. It has been stated that the porosity amounts in all nanocomposites are much higher than those in the matrix, and as the weight percentage of CNTs increases, the porosity level increases. It has been stated that this situation is due to the agglomeration of CNTs. It has also been reported that CNT clusters may prevent effective bonding between the matrix and CNTs, leading to very small cracks and increasing porosity [26].

As can be seen from the SEM images, the not very well dispersed MWCNT particles tended to aggregate and agglomerate and covered the ZA27 particles (Figure 2b). In the SEM image at 20000x magnification in Figure 2c, densely agglomerated MWCNT particles completely surrounding the ZA27 fragment are seen. In this case, the contact between the ZA27 particles is reduced. The aggregated MWCNT particles acted as a thermal barrier and somewhat prevented the thermal transfer between the ZA27 matrix material. In this case, the sintering temperature applied is insufficient, and it is considered to prevent the bond formation between the ZA27 particles at the desired level. When evaluated in terms of thermal properties, there are very important differences between the matrix material ZA27 alloy (123 W/mK) and the reinforcement element MWCNT (3000 W/mK). Another important issue is the difficulties in producing such composite structures homogeneously. It is difficult to ensure the homogeneous distribution of very small nano-sized reinforcement elements such as graphene or CNT in the metal matrix. However, the powder metallurgy technique is the most advantageous among the composite material production methods. Therefore, the powder metallurgy method was preferred in this study. The importance of the mixing process in the preparation process of composite structures emerges here. The mixing method should be chosen according to the matrix material of the composite structure to be produced and the characteristics of the reinforcement element to be used. In this study, the mechanical mixing method was applied. According to the obtained microstructure images, it can be said that it would be more appropriate to increase the applied 120 min mixing time and 300 rpm mixing speed values.

Hardness

The measured hardness values of the 0.5% MWCNT added ZA27 composite produced by powder metallurgy and the pure ZA27 sample without MWCNT reinforcement according to the Brinell method are given in the graphic in Figure 3.

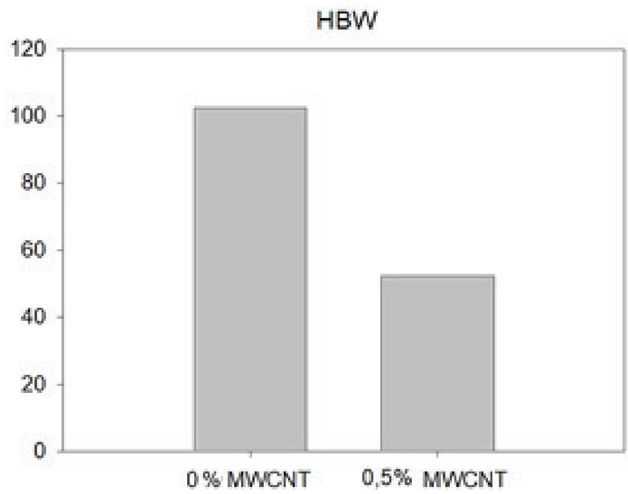

Figure 3. Hardness of test specimens.

When the graphics in Figure 3 are examined, it is understood that the hardness of the composite material has decreased significantly with the effect of MWCNT reinforced into the ZA27 matrix material. While the hardness of the pure ZA27 test sample was 102.3 HBW, the hardness value of 0.5% MWCNT reinforced ZA27 composite was 52.2 HBW. It can be said that the hardness value is reduced by half. It is thought that MWCNT particles placed between ZA27 particles prevent heat transfer during the sintering process and decrease neck and bond formation by causing a decrease in temperature between ZA27 particles. More specifically, MWCNT particles are considered to act as a heat shield and absorb some of the heat. In this case, the hardness value of the composite structure, which is weakly bonded to each other or no bond can be formed in some regions, decreased. Similar results have been expressed in different studies in the literature [20]. Since materials such as GNP and CNT have very high specific surface area values, they also constitute much volume in the composite structure, even if they are reinforced in very small amounts. In a study, it was reported that the preparation of composite mixtures by calculating the reinforcement ratios in terms of volume instead of making them in terms of weight could be a more appropriate method [27].

Machinability

Powder metallurgy is a method that allows the use of different metallic and non-metallic materials. In addition to the advantages of easily controlling the metallurgical content and density of the final product, the formability of these new types of materials with unconventional manufacturing techniques remains important for manufacturers. This study investigated the machinability of produced ZA27 and 0.5% MWCNT-ZA27 materials with EDM, and machining performance outputs such as MRR and TWR were evaluated. Figure 4 and Figure 5 show graphs presenting the changes in processing performance outputs.

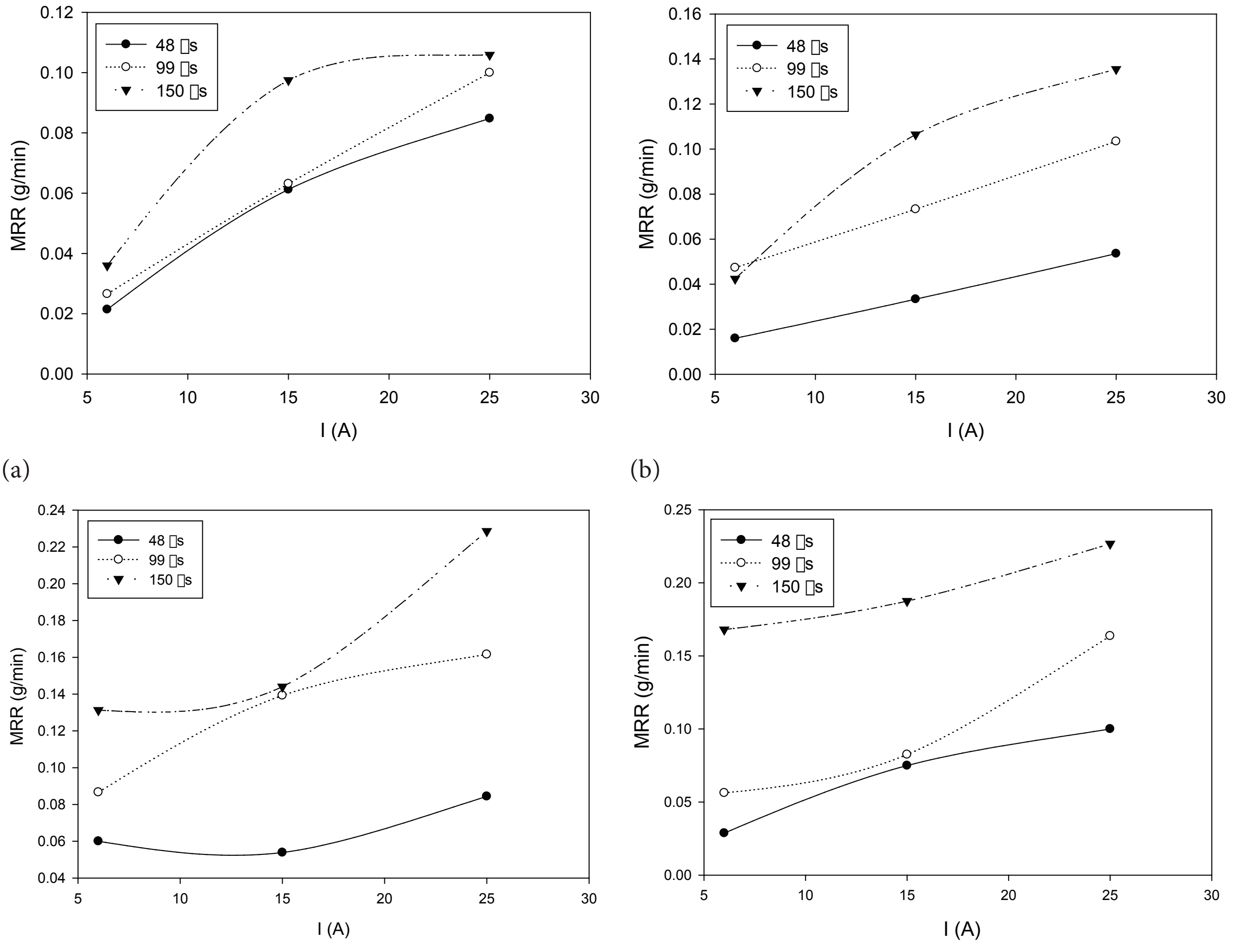

Figure 4. Variation of MRR-I-t_{on}: (a) t_{off}=99 μs constant-ZA27; (b) t_{off} = 150 μs constant-Zamac 27; (c) t_{off}=99 μs constant-%0.5 MWCNT- ZA27; (d) t_{off} =150μs constant-%0.5MWCNT- ZA27.

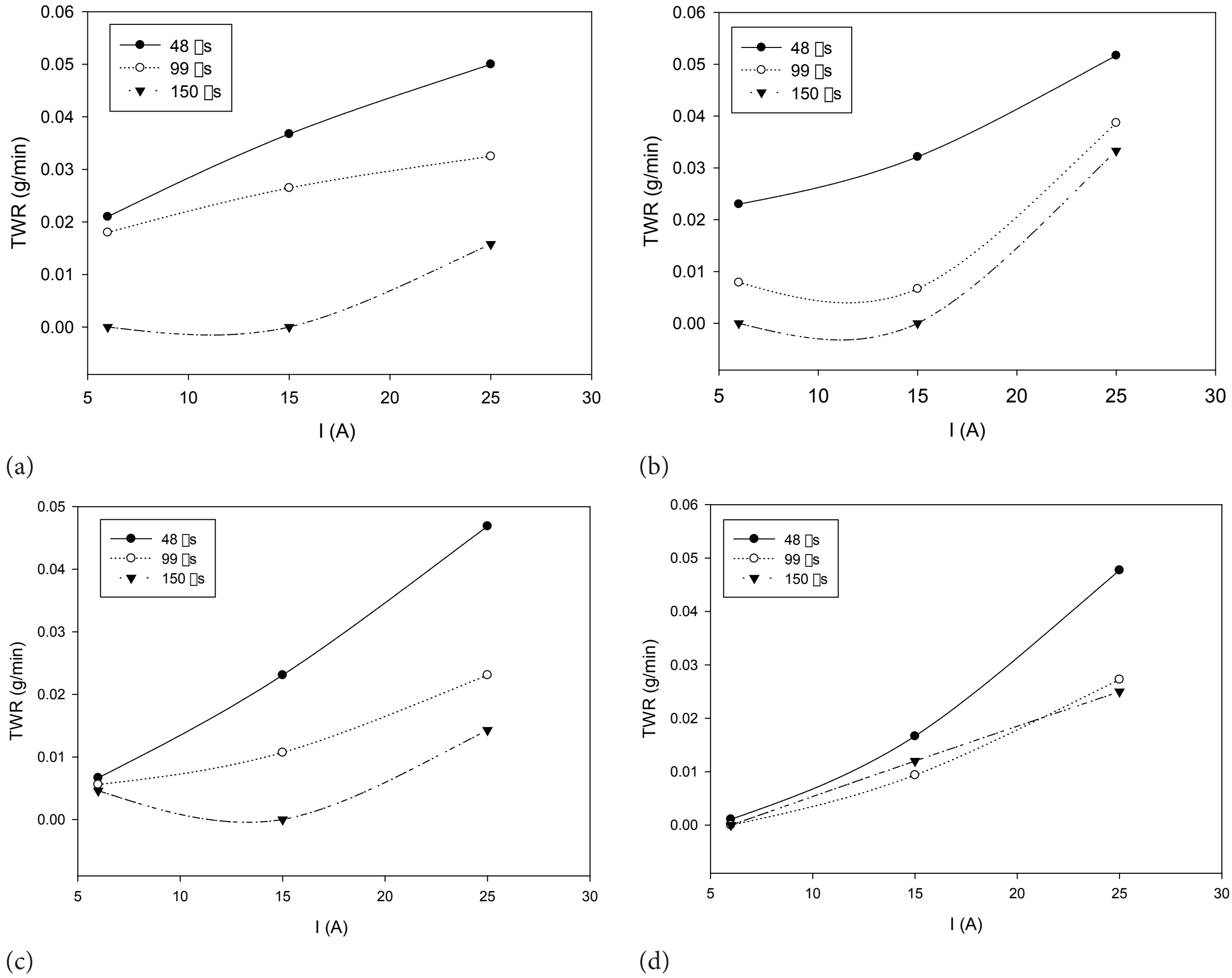

Figure 5. Variation of TWR-I-t_{on}: (a) t_{off}=99 µs constant- ZA27; (b) t_{off}=150 µs constant- ZA27; (c) t_{off}=99 µs constant-%0.5 MWCNT-ZA27; (d) t_{off} =150 µs constant--%0.5MWCNT- ZA27.

Cu electrodes are used in all machining: current and arc duration values are preferred at low, medium and high values to determine the ideal machining conditions of the material. When the graphs are examined, MRR increased mostly with increasing current and pulse time in machining (Figure 4) but decreased up to 15A current value at 150 µs pulse time of 0.5% MWCNT-ZA27 material (Figure 4-c, d), then showed an increasing trend. This situation shows that the spark discharge time is also effective depending on the discharge current value. Increasing the discharge current and the pulse duration together in EDM is the most preferred combination to increase the MRR value. The highest MRR values were found in processing 0.5% MWCNT-ZA27 (Figure 4-d). This is thought to be due to the fact that MWCNT reinforcement increases the conductivity of the material [28,29]. The lowest processing speeds were determined at 48 µs pulse value in all engravings with the same ton value. The lowest MRR value was 0.016 g/min at 6A, 48 µs t_{on} (Figure 4-b); the highest MRR value was obtained with 0.228 g/min at 25A, 150 µs t_{on} value (Figure 4-d). This indicates that more material is eroded per unit time as the ton value increases with the flow. In addition, with the increase of t_{off} value, a slight increase in MRR values was determined, which shows that the processing area is cleaned more effectively and the discharge energy is transmitted to the workpiece with less loss in time. High MRR values were obtained at 150 µs toff values.

TWR increased with increasing current values in machining and reached the highest values at 25A (Figure 5). High current values also increase the wear of the tool by melting the tip of the tool a little more during the discharge of electrons from the tool. The highest wear values were obtained in pure ZA27 materials. Lower electrode wear occurred when machining 0.5%MWCNT-ZA27 alloy. This is thought to be due to the MWCNT additive increasing the conductivity of the alloy and the quicker and easier discharge of the spark from the bottom surface of the tool. Because there is an incomparably large amount of difference between the electrical conductivity value of MWCNT nanomaterial (9800 S/m) and the conductivity values of ZA27 nanomaterial (1.72 S/m). A study in the literature reported that adding 3% by weight MWCNT into the ZA27 material increases the conductivity value of the ZA27 material 20 times [21]. The highest tool wear was obtained in the machining of ZA27 material at 25A, 0.05 g/cm^3 at 150µs impact time (Figure 5. a), and the lowest TWR was obtained in the machining of 0.5% MWCNT added material as 0.0046 g/cm^3 at 6A, 150µs t_{on} value (Figure 5.d). When evaluated in general, increasing I and ton values showed a dominant effect on TWR in an increasing trend. It can be said that the conductivity of the workpiece, especially the MWCNT reinforcement, considerably increases the spark discharge intensity.

CONCLUSION

Output parameters were compared by processing 0.5% MWCNT added ZA27 composite and pure ZA27 alloy produced by powder metallurgy method with EDM method. In addition, SEM examinations of MWCNT added materials were made and associated with the machinability results.

It was determined that porous regions were formed in both composite structures and the MWCNT particles, which did not show a fully homogeneous distribution, exhibited agglomeration behaviour in some regions and covered the ZA27 particles.

It has been determined that the MWCNT additive in EDM processing causes the formation of the magnetic field required for spark discharge in the material faster. This shows that the electrical conductivity of the doped metal increases considerably compared to the pure material. MRR increased with increasing flow and pulse time, but the machining speed of 0.5%MWCNT-ZA27 material increased significantly in all machining compared to pure ZA27 material in EDM machining of both types of materials. Based on the machinings made in the same parameter, the MRR showed the highest increase of 5.34 times in the machinings with 0.5% MWCNT added ZA27 material at 6A, 150µs t_{on} and 150µs toff values. The lowest increase was 0.9 times obtained in processing at 25A, 48µs t_{on} and 99µs t_{off} values.

ACKNOWLEDGEMENTS

This experimental study was supported within the scope of Kırıkkale University BAP project numbered 2018/043. The authors would like to thank for this support.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

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

ETHICS

There are no ethical issues with the publication of this manuscript.

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