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Research Paper / Makale

The Comparison of Performance of Electrolytic Cu and CuBe Tool Electrodes in Electric Discharge Machining of Ti6Al4V Alloy

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Abstract: The most crucial cost element of Electric Discharge Machining (EDM) is the production of tool electrode (shortly electrode). Copper, its alloys, and graphite are the most commonly used electrode materials. Selecting the proper electrode material with low production and material cost, high workpiece material removal rate (MRR) and low tool electrode wear rate (TWR) is key to reducing machining costs with EDM. In this study, the EDM performance of CuBe tool electrodes in the machining of Ti6Al4V alloy was experimentally investigated in comparison to electrolytic Cu (E-Cu) electrodes for different pulse time (t_s) and discharge current (I) settings. An increase in MRR and a decrease in TWR and relative wear (RW=TWR/MRR) were observed in machining with CuBe electrodes. However, the high raw material cost of CuBe alloy is an essential drawback in widely using these electrodes in industrial applications. A new performance index formulation is introduced for EDM applications that factor in the production cost of the electrode and its life (i.e., RW). According to our results, the CuBe could be used advantageously as the electrode material at medium current settings. However, at low and high current settings, the low raw material cost of E-Cu makes it more favorable.

Keywords: Electrical discharge machining; tool electrode; CuBe alloy; electrolytic copper; Ti6Al4V.

Ti6Al4V Alaşımının Elektro Erozyon ile İşlemesinde Elektrolitik Cu ve CuBe Takım Elektrotlarının Performansının Karşılaştırılması

Öz: Elektro erozyonla işlemede en önemli maliyet unsuru takım elektrodunun (elektrodun) üretimidir. Bakır, bakır alaşımları ve grafit en yaygın kullanılan elektrot malzemeleridir. Yüksek iş parçası işleme hızlı (MRR), düşük takım aşınma hızlı (TWR), düşük üretim ve malzeme maliyetli uygun elektrot malzemesinin seçilmesi, EDM ile işleme maliyetlerini düşürmenin anahtarıdır. Bu çalışmada, Ti6Al4V alaşımının işlenmesinde CuBe takım elektrotlarının EDM performansı, farklı bekleme süresi (t_s) ve akım boşalımı (I) ayarları için elektrolitik Cu (E-Cu) elektrotlara kıyasla deneysel olarak incelenmiştir. CuBe elektrotlarla işlemede MRR'de bir artış, TWR'de ve relatif aşınmada (RW = TWR / MRR) bir azalma gözlenmiştir. Bununla birlikte, CuBe alaşımının yüksek hammadde maliyeti, bu elektrotların endüstriyel uygulamalarda yaygın olarak kullanılmasında önemli bir dezavantajdır. Elektrodun üretim maliyetini ve ömrünü etkileyen EDM uygulamaları için yeni bir performans indeks formülasyonu tanıtıldı. Sonuçlarımıza göre CuBe, orta akım ayarlarında elektrot malzemesi olarak avantajlı bir şekilde kullanılabilir. Ancak düşük ve yüksek akım ayarlarında E-Cu'nun hammadde maliyetinin düşük olması onu daha avantajlı hale getirmektedir.

Anahtar Kelimeler: Elektoerozyon ile işleme; takım elektrodu; CuBe alaşımı; elektrolitik bakır; Ti6Al4V

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1. Introduction

Ti6Al4V alloy, one of the Ti alloys, primarily used as a biomaterial or aviation material, belongs to difficult-to-cut materials in traditional machining due to its high electrical resistivity and low heat conductivity. During EDM of Ti6Al4V, a low level of current flows through the machining gap due to the high electrical resistance of the workpiece material [1]. Moreover, the locally increased temperature due to electrical discharges on the Ti alloy surface increases the material's electrical resistance [2,3]. The low heat conductivity of the material also prevents the transfer of plasma channel heat to the work surface, causing smaller surface craters. Both facts reduce the machinability and removal rate of the workpiece material significantly. Numerous Ti6Al4V machining studies have investigated the effect of EDM process parameters (pulse time (t_s), machining current (I), dielectric type, tool electrode (shortly electrode) type, etc.) on machining performance outputs such as material removal rate (MRR), electrode (tool) wear rate (TWR), relative wear (RW=TWR/MRR), overcut, average surface roughness (R_a), surface integrity and material variance at entry and exit hole.

In recent years, Copper (Cu) and its alloys are the most commonly used electrode materials due to exhibiting favorable physical properties, ease of machining and low raw material cost [4]. The purity of the material affects the electrical conductivity (σ) of Cu electrodes, and therefore, is an essential factor for EDM performance. It is well known that the addition of other elements into the pure copper as an alloying element decreases σ [5], making electrolytic Cu (E-Cu) one of the most desirable electrode materials in EDM processes. The use of graphite in the EDM process as an electrode material is much more limited than the use of copper and its alloys since graphite is highly expensive (about three times more costly than the E-Cu). Furthermore, it exhibits low electrical and thermal conductivities, more machining difficulties of complex electrode forms, and much less know-how about its use. Copper-beryllium (CuBe) alloys, commonly used in the aviation industry and electric contact applications, are among the strongest copper alloys. Although the CuBe alloys are more expensive than the E-Cu, their good conductivity, high melting temperature, high wear resistance and good machinability make them stand out as a suitable electrode material. Our literature survey revealed no published study examining the use of CuBe alloys compared to E-Cu as electrode material in EDM machining of Ti6Al4V alloy, factoring in the material cost as the EDM performance outputs.

The desired machining performance outputs are described in high MRR, low tool TWR, low RW and low average surface roughness (R_a). High TWR and RW are undesirable since they indicate rapid tool electrode shape degeneration. Two main problems of the EDM process are the high cost of the electrode production process and the high electrode wear [6,7]. In recent years, researchers have mainly focused on low production costs and better EDM performance outputs. The approach for lowering the EDM process cost is basically to choose Cu (or its alloys) as electrode material that possesses low raw material and production costs as well as high MRR and electrical wear resistance (i.e., low TWR and RW) [8,9].

Hasçalık and Çaydaş [10] performed an investigation on EDM of Ti6Al4V alloy by using Al, Cu and graphite electrodes. They demonstrated that TWR, MRR and Ra increased with t_s and I values. In Shabgard and Khosrozadeh [11], the EDM of Ti6Al4V was examined by mixing carbon nanotube (CNT) powders into the dielectric fluid. It was found that MRR decreased with the addition of powders, but it increased with the use of high t_s settings. The t_s and I were experimentally shown to be the most significant parameters that affected the electrode wear and machining time. In Li et al. [12], the surface finish and the surface microstructure characteristics of Ti6Al4V alloy were enhanced by using a Cu-SiC composite electrode. An increase in I resulted in a considerable rise in MRR because of the rising temperature of the machined material. The electrode wear was found to be inversely proportional to increasing t_s. The highest Ra value was obtained by using the highest t_s and I settings. The microcrack formation on the machined surface increased when the pulse-off time (tp) was increased, according to Li et al.'s study [13]. In Strasky and Janeceketc's study [14], the EDM was conducted as a surface treatment process of Ti6Al4V alloy for biomedical applications. They revealed that R_a was high and a carbon enriched surface was formed at high I values. In the Verma and Sahu study [15], the Ra increased with increasing I and ts and decreased with increasing dielectric flushing pressure in the machining of Ti6Al4V alloy. Ünses and Çoğun [16] experimentally showed that the graphite powder addition to the dielectric in EDM die sinking and EDM drilling applications of Ti6Al4V in the aerospace industry enhanced the machining performance and reduced the machining cost. Koua and Han [17] compared the machinability of Ti alloy by die-sinking EDM and EDM milling with and without rotating copper electrodes at the same machining parameters. They had stated that the rotational movement of the electrode eliminated the automatic retraction movement of the electrode for the removal of machining residues at the machining gap resulting in a higher MRR compared to the EDM applications without rotary electrodes.

In our study, the EDM performance outputs (MRR, TWR, RW and R_a) were experimentally investigated using E-Cu and CuBe alloy electrodes under different machining parameter settings (more specifically, t_s and I). Moreover, a new performance index was proposed that uses the electrode cost and RW. An electrode production cost analysis was performed using the index. A choice is made between E-Cu and CuBe for exemplary machining parameters using the experimental results and the proposed index.

2. Experimental Procedure

In this study, Ti6Al4V alloy samples with 40x20x10 mm dimensions were used as workpiece material. The E-Cu and CuBe electrodes were prepared by cutting a 30x15 mm rectangular bar into 10 mm length. The machining was performed on the 40x20 mm surface of the workpiece using the 30x15 mm surface of the electrode. The properties of electrode and workpiece materials are given in Table 1.

The machining parameters are given in Table 2. The experiments were conducted using M25A EDM Die-Sinking Machine Tool manufactured by FURKAN Corp. in Turkey. Kerosene dielectric with 0.2 bar side flushing pressure was applied throughout the experiments. The samples were EDM machined at a depth of 0.5 mm.

Table 1. The properties of electrode and workpiece samples

Material	Composition (wt.%)	UTS (MPa)	σ_y (MPa)	Hardness (HBN)	Melting Temp. (ºC)	Thermal Conductivity (W/mK)	Electric Conductivity (Siemens/m)
E-Cu	99.9 Cu	360	320	120	1084	386	5.80E+07
CuBe	Cu, 1.6 Be	750	650	272	955	260	9.86E+06
Ti6Al4V	Ti, 6 Al, 4 V	965	895	342	1604	7.1	5.80E+05

The resulting reliability is provided by repeating each experiment multiple times. The machined workpiece and worn electrode volumes were calculated by measuring the weight losses after machining. The MRR (mm^3/s) and TWR (mm^3/s) were calculated by dividing volumetric losses by machining time. R_a values were measured by using Mitutoyo Surftest SJ-201P type portable device. Microstructural investigations were done by using an Olympus-Gx metallographic microscope. The electric conductivity of the samples was tested with Autosigma 3000 DL instrument. The hardness measurements were performed with MHT 150-RB digital hardness measurement device.

Table 2. EDM parameters used in the study

Parameters	Settings
Pulse time, t_s (μs)	25, 50, 100
Pulse-off time, t_p (μs)	50
Discharge current, I (A)	3, 6, 12
Dielectric liquid	Kerosene
Dielectric flushing type	Side
Flushing pressure (bar)	0.2
Machining depth (mm)	0.5
Polarity	Electrode (-)

3. Results

3.1. Variation of Performance Outputs with Machining Parameters

The higher I and t_s are yielded higher MRR for E-Cu and CuBe electrodes (Figure 1a) due to large amounts of material removed during the melting and evaporating phenomena by the discharge pulse with high energy (discharge energy = discharge time x I). The deep crater formations with large diameters caused by the high energy discharges with high I and t_s settings exhibited poor surface quality and higher Ra values, as was recorded in Figure 1d. The higher MRR values observed with CuBe electrodes than E-Cu electrodes were attributed to the lower electrical conductivity of CuBe electrodes than the E-Cu electrodes. The low electrical conductivity needed a narrower machining gap to start the ionization of dielectric fluid (the first phase of discharge formation). The narrower machining gap provided the early start of electric discharge [18, 19] (i. e., short discharge delay time), yielding the use of the higher percentage of t_s in discharging. The long duration discharges in the machining gap provided much more effective removal of material from the workpiece surface.

The RW showed a significant decrease at higher I for both electrode types for all t_s settings (Figure 1c) due to the rapid increase of MRR to TWR with increasing I (Figure 1b). Moreover, higher ts only slightly increased the RW due to the rise in TWR for both types of electrodes. The high RW (in the range of 10.8% to 140%) indicated rapid electrode wear and geometric shape degeneration (especially at low I settings). The high RW was due to the low thermal conductivity of Ti6Al4V workpiece material, which limited the growth of melting craters formed by electric discharges, yielding low MRR values. The CuBe electrodes yielded lower RW values than E-Cu electrodes, which indicated slower electrode wear rates and shape degeneration. All and all, these results show that CuBe alloy is a better performance electrode material compared to E-Cu. It has high MRR and low RW values. The R_a values in the range of 1.47-8.3 mm (Figure 1d) found in this study are acceptable for the machining settings and electrode types commonly used for most industrial applications, especially for difficult-to-machine Ti6Al4V alloy.

3.2. Electrode Cost Analysis and Performance Index

The labor and amortization cost of cutting into size and milling of the machining surface of the electrode and the raw material cost for the electrodes are given in Table 3. The service life (lifetime) of an electrode is inversely proportional to the RW of the electrode (i.e., the smaller the RW value, the longer the electrode life). In this study, a performance index PI was defined as PI=MRR [mm^3/min]/{(production cost of an electrode [€/electrode])×TWR [mm^3/min]}. Choosing an electrode material with a high PI (i. e., high MRR, low production cost and low TWR) will be much suitable to lower machining cost.

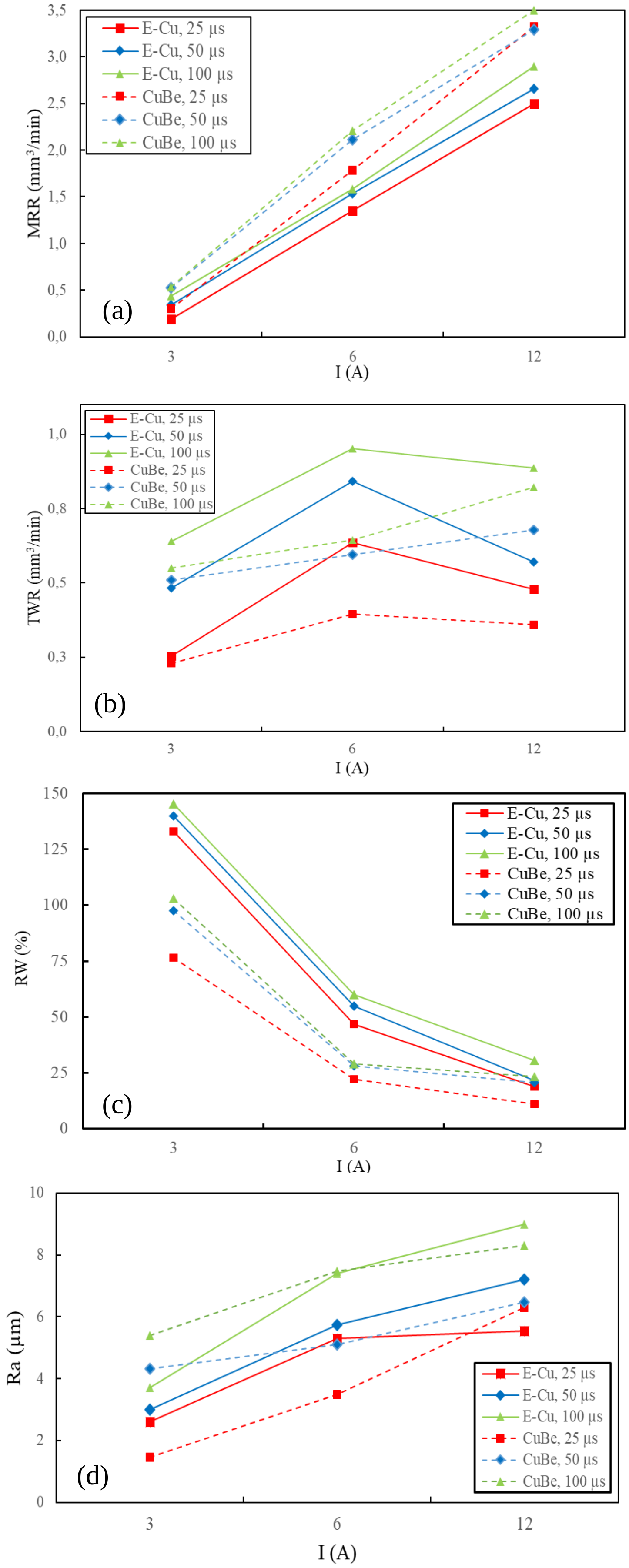

Figure 1. Variation of machining performance outputs for E-Cu and CuBe electrodes with varying I and t_s (a) MRR, b) TWR, c) RW, and d) R_a

Since RW=TWR/MRR, the PI formula becomes 1/{(cost of an electrode [€/electrode] ×RW]. Table 3 revealed that the E-Cu electrode had the highest PI values for I=3A and 12A settings, whereas the CuBe electrode yielded higher values for the I=6A setting used in this study. The high PI of the CuBe electrode was primarily due to its low RW values (Figure 1c), whereas the high PI of the E-Cu was due to its low raw material cost. One can conclude that E-Cu is the primary choice for economic EDM of the Ti6Al4V workpiece under low and high current settings, whereas CuBe is preferable for medium current settings.

Table 3. The cost and PI of the electrodes used in the experiments.

Electrode	Raw material cost (€/el.)*	Cutting and milling cost (€/el.)	Total cost (€/el.)	PI								
				t_s (µs), I_d=3 A			t_s (µs), I_d=6 A			t_s (µs), I_d=12 A		
				25	50	100	25	50	100	25	50	100
E-Cu	0.36	0.45	0.81	0.93	0.88	1.23	1.85	2.28	2.05	6.85	5.87	4.11
CuBe	0.97		1.42	0.92	0.71	0.68	3.2	2.51	2.43	6.4	3.35	3.06

4. Conclusion

In this study, the following conclusions have been drawn regarding the effect of using the electrolytic-copper (E-Cu) and copper-beryllium (CuBe) tool electrode materials on machining performance outputs (namely material removal rate (MRR), tool electrode wear rate (TWR), relative wear (RW=TWR/MRR), average surface roughness (R_a)) and machining cost of Ti6Al4V alloy workpiece:
- Higher I and t_s increased the MRR for both E-Cu and CuBe electrodes due to the high material removed by melting and evaporating phenomena by a discharge pulse with high energy. The higher MRR values were observed when machining with CuBe electrodes than the E-Cu electrodes, which was attributed to the lower electrical conductivity of CuBe electrodes.

- The CuBe electrodes yielded lower RW values than E-Cu electrodes, which indicated slower electrode wear rates and shape degeneration.
- All samples machined at high I settings displayed higher R_a due to the formation of wider and deeper craters because of high-energy discharges formed in the machining gap.

- CuBe alloy can be considered a better performance electrode material than the E-Cu, considering its higher MRR and lower RW values. The performance index introduced in this study, PI=1/[(electrode cost) ×RW], revealed that the E-Cu electrode is the primary choice for EDM of Ti6Al4V workpiece when factoring in the electrode cost at both low and high current settings. The CuBe electrode is the preferred choice only for medium current settings.

Authors' Contributions

LU, HBÖ and FB performed the experiments. CÇ and İU analyzed the results and wrote the manuscript. The authors read and approved the final manuscript.

Conflict of Interest

There is no conflict of interest in this study.

Kaynaklar

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