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Improvement of Electric Discharge Machining (EDM) Performance of Ti-6Al-4V Alloy with Added Graphite Powder to Dielectric

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Ti-6Al-4V is a well-known Ti alloy widely used in the aerospace industry and belongs to the group of difficult-to-machine materials. It is less suitable for both conventional chip removal (machining) techniques and electric discharge machining (EDM). The very low material removal rate (MRR) of the Ti alloys during the EDM process causes prohibitively long machining durations. The goal of this study was to improve the EDM performance of the Ti-6Al-4V alloy by the addition of graphite powder into the kerosene dielectric liquid. The EDM performance was quantified by MRR, tool electrode wear rate (EWR), relative wear (RW), surface roughness and texture properties. The experiments conducted have shown that the use of graphite powder mixed with the kerosene dielectric (GPMKD) during machining considerably increases the MRR, improves the R_a *and* $R_{z(DIN)}$ *surface roughness and decreases the RW. 3D topographic views of the machined workpiece surfaces attained with GPMKD revealed uniformly distributed surface valleys and peaks over the surface and peaks with short and round tops since the discharge energy of a spark is distributed over a large area at the machining gap. The experimental results strongly indicate the adaptability of the proposed technique to EDM die sinking and EDM drilling applications of the Ti-6Al-4V alloy in the aerospace industry. The ED machining performance of Ti-6Al-4V alloy using GPMKD is also compared to that of AISI 1040 steel, which is commonly used in EDM applications.*
Key words: electric discharge machining (EDM), Ti-6Al-4V, graphite powder, material removal, tool electrode wear, roughness, 3D surface topography

Highlights
- *The use of graphite powder mixed kerosene dielectric (GPMKD) in Ti-6Al-4V machining increases the material removal rate (MRR).*
- *GPMKD use resulted in lower peak-to-valley heights than the kerosene dielectric considering surface topographies.*
- *The machined surfaces were free of carbon contamination in the GPMKD experiments.*
- *Graphite powder used in this study is much cheaper than other metallic and non-metallic powders used in the literature.*

0 INTRODUCTION

Electric discharge machining (EDM) is one of the non-traditional machining methods that is commonly used to produce die cavities by the erosive effect of electrical discharges. The success of EDM is associated with its capability of machining workpieces of high hardness and complex shapes that cannot be machined by conventional chip removal methods. This method is especially effective in machining hard die steels, complex cavities and small workpieces.

Ti-6Al-4V is a well-known Ti alloy widely used in the aerospace industry in jet engines, particularly in the disk and fan blade components of the compressor. Ti-6Al-4V has a 7 to 10 times higher electrical resistance, a 7 to 8 times lower heat conductivity and a 10 % to 15 % higher melting temperature than the AISI 1040 steel which is widely used in the production of machine elements and die applications. Ti-6Al-4V belongs to the group of difficult-to-cut materials in traditional machining. The two main problems in the traditional machining of Ti-6Al-4V are as follows:

a) The heat generated during cutting action cannot be easily dissipated since Ti-6Al-4V is a poor heat conductor. The heat is concentrated on the cutting edge causing very short tool life.
b) The Ti-6Al-4V has a strong alloying tendency with cutting tool materials causing palling, welding and smearing on tool surface especially at high cutting temperatures.

For these reasons, cutting is performed at low cutting speeds to ensure a reasonable tool life. The economical machining rates of the Ti-6Al-4V vary between 20 mm^3/min and 8000 mm^3/min depending on machining operations, cutting tool characteristics, feed rates, cutting speeds and depth of cuts. The EDM of Ti alloys is also difficult as compared to Ni based super alloys due to high electrical resistivity (low electrical conductivity). During EDM of Ti-6Al-4V, 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 electrical resistance of the

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material [2]. The low heat conductivity of the material also prevents the transfer of plasma channel heat to the work surface thus causing smaller surface craters. Both facts reduce the machinability and material removal rate (MRR) of the material significantly. Asokan et al. [1] used EDM for drilling holes in Ti-6Al-4V with a Cu tool electrode and deionized water dielectric. They concluded that the current, pulse time (pulse on time) t_s, pause time (pulse off time) t_p and capacitance affected the MRR and the dimensional accuracy. Soni and Chakraverti [3] experimentally investigated the effects of discharge current i_d and tool electrode rotational speed (0 rpm to 1000 rpm) on MRR, tool electrode wear rate (EWR) and average surface roughness (R_a) of the Ti alloy using commercial grade kerosene without a powder addition. They found that the increasing rotational speed of the Cu-W tool electrode improved the MRR, but increased the EWR and R_a. Chen et al. [4] investigated the effects of deionized water and kerosene dielectric on machining performance of the Ti-6Al-4V alloy using a Cu tool electrode. The study revealed that the deionized water resulted in higher MRR and lower EWR than the kerosene. The lower MRR with the kerosene dielectric was attributed to: i) the formation of a TiC layer on the workpiece surface which has higher melting temperature than the workpiece material, ii) the formation of a C layer on the tool electrode surface causing passivation of electric discharge phenomena. Mhatre et al. [5] experimentally investigated the electric discharge drilling characteristics of Ti-6Al-4V using a commercial EDM dielectric IPOL. The i_d is found to be the most significant parameter affecting the MRR, the dimensional accuracy and the surface integrity of the drilled hole. They also claimed that increasing the i_d and the pulse voltage increases the MRR to a certain extent and decreases the EWR, while increasing t_s causes a reduction in the EWR.

Numerous research studies have shown that using a powder mixed dielectric EDM (P-EDM) process can improve the surface roughness, increase MRR, and reduce EWR and relative wear (RW=EWR/MRR). Addition of electrical conductive powder into the dielectric leads to a bridging effect and reduces the insulating strength of the dielectric fluid, thus forming a discharge channel more easily [3] and [6]. The bridging phenomena results in the multisplitting of one discharge occurrence over a larger area in the machining gap during a pulse cycle time. Thus, the energy of a pulse is shared across multiple discharges (with less energy), which form shallow and large diameter craters on the surface. These craters result in a better surface roughness and lower peak-to-valley heights in the machined surface profiles. In one of the earlier studies in the field, Jeswani [7] investigated the effects of adding 4 g/l graphite powder into the kerosene dielectric during machining of mild steel with a copper tool electrode. An increase in MRR and a decrease in EWR and RW were reported. Uno and Okada [8] and Uno et al. [9] mixed Si and Ni powder into the dielectric to coat the Al-bronze die surface. The increasing Ni powder concentration (C_p) resulted in smaller crater dimensions and a thicker re-solidified layer on the die surface alloyed with Ni. They also obtained a hard TiC layer on the tool steel surface by using a Ti tool electrode and graphite mixed kerosene under reverse electrode polarity (to increase the wear of Ti tool electrode). Ming and He [10] stated that the addition of conductive and inorganic-oxide powders into kerosene decreases the ionization voltage of the dielectric and increases the machining gap. Cogun et al. [11] experimentally studied the effects of adding graphite and non-conductive boric acid powder into kerosene on MRR, EWR, RW, R_a and surface hardness for the Cu tool electrode-steel workpiece pair. The graphite powder C_p and the t_s were the two machining parameters found to strongly effect MRR and EWR. Furutani et al. [12] mixed Ti powder into the dielectric to form a thick TiC layer on metal surfaces using small Cu wire or rotating disc electrodes. They realized that the higher Ti powder C_p resulted in harder TiC coatings. In Prihandana et al. [13], the silver-tungsten workpiece was micro-drilled (holes with 300 μm and 500 μm depth) with a tungsten tool electrode at 10 g/l graphite powder C_p in the kerosene. They reported a five times higher MRR than for pure kerosene. Reddy et al. [14] investigated the machining characteristics of a PH17-4 stainless steel workpiece using surfactant (non-ionic SPAN20) and graphite mixed commercial EDM oil. They claimed an increase in electric conductivity of the dielectric fluid with increasing concentration of the surfactant. The maximum MRR has been achieved at 6 g/l surfactant and 4.5 g/l graphite powder concentration settings.

The literature survey reveals that little work has been carried out on the P-EDM of Ti-6Al-4V alloy. Lin et al. [15] used a hybrid process (EDM+USM (ultrasonic machining)) to machine the Ti-6Al-4V. The SiC powder added to deionized water and kerosene was used as a conductive powder in the dielectric for EDM and as an abrasive for the USM process. It is reported that increasing the SiC powder concentration up to 90 g/l improved the MRR significantly. On the other hand, a very high C_p resulted in the accumulation of excessive powder in the machining gap resulting in frequent arc pulses (undesirable) and low MRR.

The kerosene with SiC powder led to better surface roughness than the deionized water with SiC powder. Chow et al. [16] investigated the effects of Al and SiC powder additions to the kerosene dielectric on MRR, EWR, R_a and discharge voltage waveforms of the Ti-6Al-4V workpiece. It is reported that the MRR was increased and R_a was decreased for P-EDM cases. It was found that the SiC powder mixed kerosene resulted in a higher MRR than that of Al powder, whereas the lowest R_a was experienced in Al powder mixed cases. In another work of Chow et al. [17], the MRR and EWR performance of Ti-6Al-4V were tested for the deionized water dielectric with and without SiC powder addition by using a rotational copper disk tool electrode. The highest MRR and the lowest EWR were obtained when 25 g/l SiC powder is mixed with deionized water. However, better R_a and surface texture were reported for the SiC powder mixed cases compared to using the pure deionized water. Rival [18] experimentally investigated the effects of SiC powder addition (2 g/l to 6 g/l) into kerosene on MRR, EWR and R_a for a Ti-6Al-4V workpiece and Cu-W tool electrode. He found that the MRR and R_a values were higher with higher i_d for the powder mixed kerosene experiments. The lowest R_a was obtained at 2 g/l SiC powder concentration. In Yasar and Ekmekci [19], the effects on surface topography of the Ti-6Al-4V workpiece were investigated when SiC powder was added into deionized water and kerosene. In their experimental work, the SiC powder C_p, the powder particle size, t_s and i_d were determined as the key parameters affecting surface topography. Homogenous surface topographies with small surface craters were observed on workpiece surfaces machined with SiC added dielectrics.

1 PURPOSE OF THE STUDY

The literature survey revealed that a P-EDM study on the effect of a graphite powder mixed dielectric on machining performance of Ti-6Al-4V, an alloy seeing growing use in the aerospace industry, has not been reported on so far. The authors of this work believe from their past experience [11] that adding graphite powder to the dielectric can significantly improve specific machining performance outputs of Ti-6Al-4V alloy such as MRR, EWR, RW and surface roughness. Moreover, the proposed graphite powder in this study is ~70% cheaper than the cheapest metallic and non-metallic powders used in the literature (like SiC, Al, Ni). This makes the graphite powder economically attractive with respect to the others. Moreover, the lower density of the graphite powder (2.1 g/cm³) than the other powders (ρ_{SiC} = 3.2 g/cm³, ρ_{Ni} = 8.9 g/cm³, ρ_{Al} = 2.7 g/cm³) makes the formation of a homogenous suspension of the powder in the dielectric easier (due to the same particle size distributions). Following these considerations, we study the effects of adding graphite powder to kerosene on the MRR, EWR, RW and machined workpiece surface characteristics ((R_a, $R_{z(DIN)}$ and surface topography) depending on t_s, i_d and the dielectric flushing pressure P_d.

2 EXPERIMENTAL SETUP AND METHODS

The electric discharge machine used in this investigation is FURKAN EDM M25 Model die sinking machine with EDM25A generator. The pulse generator is an iso-pulse type with 80 V open circuit voltage.

In the first group of experiments, the kerosene (KD) was used. In the second group of experiments, graphite powder smaller than 37 µm particle size was mixed into kerosene (graphite powder mixed kerosene dielectric, GPMKD). Both the KD and the GPMKD experiments were conducted in a self-made machining tank with 40 cm × 55 cm × 24 cm dimensions made of 1.5 mm thick stainless steel sheets (Fig. 1). In order to maintain a homogenous suspension of graphite powder in the tank during tests, a flush mixing was applied by means of two parallel spaced (at the two bottom sides of the tank) 12 mm diameter Cu pipes with 2.4 mm diameter holes on it. The dielectric was sucked from the bottom level of the tank by means of a pump. One of the two branches of the pump exit was directed to the Cu pipes for homogenous mixing of the powder. The other branch was directed towards the machining gap (side flushing) for flushing the machining debris away. A manometer and an adjustment vane were mounted to the flushing branch to set the flushing pressure.

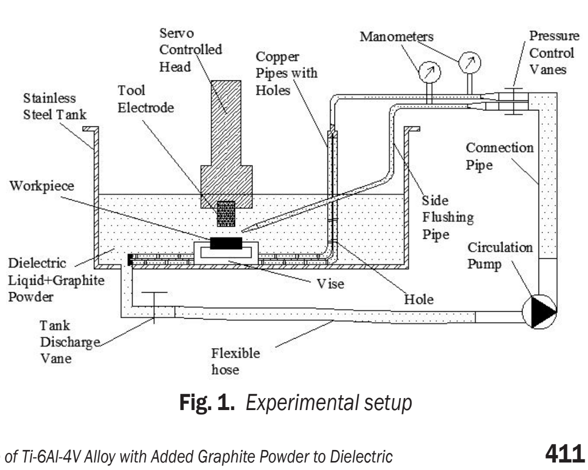

Fig. 1. *Experimental setup*

The graphite powder C_p to be used in the experiments was determined by a set of experiments conducted at t_s=100 µs, i_d=12 A, P_d=0.1 bar (Exp. 13) machining settings for C_p at 1 g/l, 3 g/l, 5 g/l, 10 g/l and 15 g/l. The machining duration was 70 minutes. Compared to the KD experiments (Fig. 2a and b), negligibly slight deviations in MRR and EWR values were observed at both 1 g/l and 3 g/l C_p values. At C_p=5 g/l, the MRR is almost doubled with respect to the KD. A very slight increase in MRR was observed at C_p=10 g/l and C_p=15 g/l (Fig. 2a) with respect to C_p=5 g/l. No significant difference in EWR values between KD and GPMKD with C_p=5 g/l was observed. However, the EWR increased noticeably for C_p=10 g/l and C_p=15 g/l (Fig. 2b). The R_a value was decreased with increasing C_p up to the 5 g/l level and no further improvement was observed above this particular level (Fig. 2c). Thus, C_p=5 g/l was selected as the level giving the best machining performance outputs among the tested C_p levels. In the literature, the elevated MRR values of various grades of steel and silver-tungsten workpieces with a range of 4 g/l to10 g/l graphite powder C_p in the kerosene [7], [11] and [13] and at 4.5 g/l graphite powder + 6 g/l surfactant concentration in the EDM oil [14] were also reported.

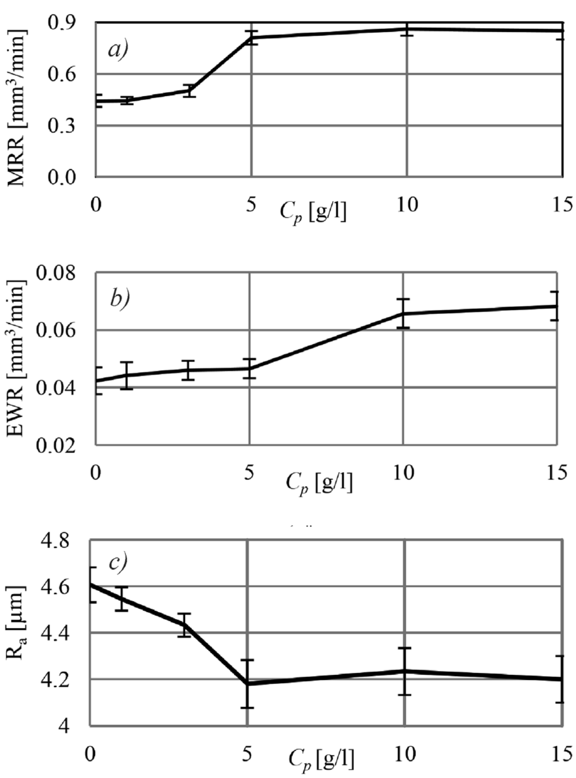

Fig. 2. *The effect of C_p on: a)* MRR, *b)* EWR *and c)* R_a

In the experiments, the workpiece material used was a Ti-6Al-4V Grade 5 alloy (90% Ti, 5.9% Al, 4% Va, 0.07% Fe, 0.02% C). The physical, mechanical, electrical and thermal properties of the alloy are given in Table 1. The workpieces were cut from a 30 mm diameter bar at 6 mm lengths. The bottom and top circular surfaces were finished using a fine emery paper. The workpieces were cut-off at their plane of symmetry to form two identical halves (Fig. 3). The two halves were contacted to each other to form a solid workpiece during experiments by using a simple vise. At the end of the machining, the separated halves facilitated easy surface roughness measurement since the mechanical contact stylus of the device should move along (traverse) the ED machined surface in horizontal. The same size of AISI 1040 steel (0.38% C, 0.6% Mn, 0.04% P, 0.05% S) workpieces (properties given in Table 1) were also prepared and ED machined to compare the MRR, EWR, R_a and RW values with that of Ti-6Al-4V. The electrolytic copper tool electrodes used in the experiments were in a cylindrical shape cut from a 14 mm diameter copper bar. The tool electrodes were 13 mm in diameter and 40 mm in length.

Table 1. *Properties of the Ti-6Al-4V alloy and the AISI 1040 steel*

Properties	Ti-6Al-4V [20]	AISI 1040
Density [g/cm³]	4.43	7.85
Brinell hardness [-]	334	163
Yield/ UT Strength [MPa]	1040/1080	361/585
Elasticity module [GPa]	113.8	200
Poisson ratio [-]	0.34	0.31
Electrical resistance [Ω·cm]	$178e^{-6}$	$171e^{-7}$
Spec. heat capacity [J/(kg·K)])	526	486
Heat conductivity [W/(m·K)]	6.7	50.7
Melting point [°C]	1604 to 1660	1400 to 1450

In this study, the preliminary experiments with t_s and i_d values lower than 50 µs and 6 A, respectively, indicated prohibitively long machining cycles. On the other hand, extremely poor surface roughness prevented us from using t_s and i_d values above 100 µs and 12 A, respectively. In the experiments, a long t_p (100 µs) was selected to allow more time for the removal of heat from the machining medium both via dielectric circulation (convective heat transfer) [21] and conductive heat transfer. The machining parameters and experimental design are given in Tables 2 and 3. Every experiment was repeated three times and the average of the measurements was used in the analysis. Error bars were also added to the graphical representation of the results to depict the fluctuations in the measurements. Weight loss of the tool electrodes and workpieces were determined by taking initial and final (after machining) weights of the tool electrodes and workpieces using a HANA HG-1 type digital scale with 0.005 g accuracy. The weight losses were used to calculate the MRR, EWR and RW. Workpiece R_a and $R_{Z(DIN)}$ (average of the highest peak-to-valley measurements found for each cut-off length) measurements were performed using a portable Rank Taylor-Hobson Surtronic 3+ HB-103 stylus tracing instrument. The average of the measurements taken at six locations was used in the analysis.

The experiments were intentionally carried out using the arc control mode of the pulse generator at "medium suppression" level to observe the effects of machining parameters (i_d, t_s, P_d) and GPMKD on machining stability (regime). This setting level doesn't completely prevent the formation of arcs. However, we retracted the tool electrode in a timely manner (Table 2) to reduce the risk of tool electrode and workpiece surface damage due to arcing.

3D topographic views of the machined workpiece surfaces were generated by using a photometric stereo technique. A Point Grey Dragon Fly camera was used as the photographic capture system. The 2 mm × 2 mm surfaces were selected from the machined workpiece to obtain the topographic views. The 0.5 mm × 0.5 mm areas on the 2 mm × 2 mm views were magnified for closer examination of the surface characteristics. A Mitutoya MF176 toolmakers microscope was also used to examine the formed surface craters' characteristics.

Fig. 3. *A machined Ti-6Al-4V workpiece*

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Effect of GPMKD on MRR

The MRR increased with increasing t_s and P_d for both KD and GPMKD experiments (Fig. 4). The longer t_s resulted in a higher amount of energy transfer to the workpiece surface leading to higher amounts of work material removal by melting and evaporation phenomena [11]. For all machining settings, the MRR was increased by the use of GPMKD (Fig. 4), which was attributed to the following factors:

a) GPMKD reduces the electric resistance of the machining gap enabling high current (energy) flow through the gap and high amount of material removal from the workpiece craters [6].
b) The GPMKD widens the gap eliminating the difficulties in dielectric circulation and removal of debris in the machining medium, which in turn results in a higher number effective discharges [21] leading to higher MRR.

The second factor is more dominant in increasing MRR since Ti-6Al-4V has an extremely low thermal conductivity (proportional to the electrical conductivity) causing only small workpiece craters.

In this study, a 25 % to 104.3 % increase in Ti-6Al-4V MRR is achieved by using GPMKD for the machining settings used. In the literature, a 60 % to 500 % increase in MRR of non-Ti alloy workpieces (such as mild steel, 1040 steel and stainless steel) was reported when using GPMKD [7], [11] and [13]. Yet, only a 28.5 % to 60 % increase in Ti-6Al-4V MRR using Al or SiC powder mixed kerosene or deionized water was reported [15] to [17]. Therefore, the addition of graphite powder into kerosene resulted in a higher Ti-6Al-4V MRR than the addition of Al and SiC powders into the dielectrics.

Table 2. *Experimental settings*

Machining Parameter	Setting
Discharge current, i_d [A]	6, 12
Pulse (on) time, t_s [μs]	50, 100
Pause (pulse-off) time, t_p [μs]	100
Work duration [s]	1.6
Retraction duration [s]	0.8
Dielectric pressure, P_d [bar]	0.1, 0.4
Dielectric liquid	KD, GPMKD
Dielectric flushing type	side
Polarity	tool electrode (+)
Machining depth [mm]	0.7

3.2 Effect of GPMKD on Surface Roughness and Topography

Referring to Fig. 5, an increase in P_d does not lead to a significant difference in the values of R_a when comparing the KD and GPMKD experiments. It can also be seen that varying t_s has a smaller effect on R_a in the KD experiments. The higher P_d yielded a stable machining regime and less carbon accumulation on the surface. Destruction of the workpiece and tool electrode surface was observed in the KD experiments when improper t_s and t_p values were selected for the used i_d values. The typical type of destruction was the lamination of the Cu tool electrode due to high temperatures generated in the gap, since Cu has lower melting temperature than the Ti-6Al-4V.

Table 3. *Experimental design*

Exp. no	Dielectric	t_s [μs]	i_d [A]	P_d [bar]
1	KD	50	12	0.1
2	KD	50	12	0.4
3	KD	50	6	0.1
4	KD	50	6	0.4
5	KD	100	12	0.1
6	KD	100	12	0.4
7	KD	100	6	0.1
8	KD	100	6	0.4
9	GPMKD	50	12	0.1
10	GPMKD	50	12	0.4
11	GPMKD	50	6	0.1
12	GPMKD	50	6	0.4
13	GPMKD	100	12	0.1
14	GPMKD	100	12	0.4
15	GPMKD	100	6	0.1
16	GPMKD	100	6	0.4

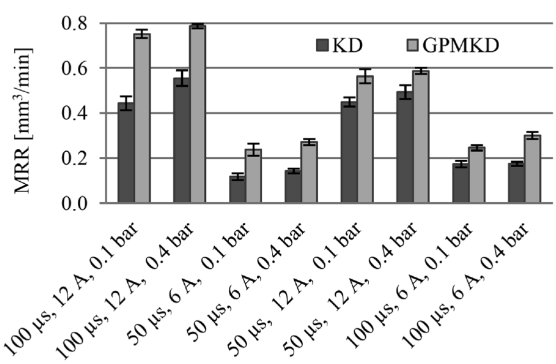

Fig. 4. *Effect of* GPMKD *on* MRR

The high temperature in the gap was due to poor heat conductivity of the Ti-6Al-4V workpiece **[1]**. The laminated tool electrode surface also causes deterioration of the workpiece surface. Accordingly, the GPMKD experiments resulted in lower R_a values (Fig. 5) and shinier surfaces compared to the KD experiments. The main reasons for this result are the enlarged heat discharge area forming large diameter and shallow craters **[6]**, **[11]** and **[16]** and the accumulation of less carbon black (due to less frequent arc formations) on the surface.

In this study, a 2.4 % to 18.3 % decrease in R_a is observed by using GPMKD for the machining settings used. In the literature, a 5.4 % to 67 % decrease in R_a in machining of the 1040 steel workpiece by using GPMKD was reported **[11]**. However, R_a decreases of at most 25 % **[15]**, 30.5 % **[16]**, 35 % **[17]** and 27 % **[18]** have been reported in the machining of Ti-6Al-4V with kerosene+SiC powder, kerosene+Al powder, deionized water+SiC powder and kerosene+SiC powder mixtures, respectively. So, the R_a values measured in this study (3.8 mm to 4.7 mm) in the machining of Ti-6Al-4V with GPMKD are consistent with the reported findings in the literature (2.5 mm to 3.6 mm) for the same workpiece but for different dielectric and powder mixture combinations.

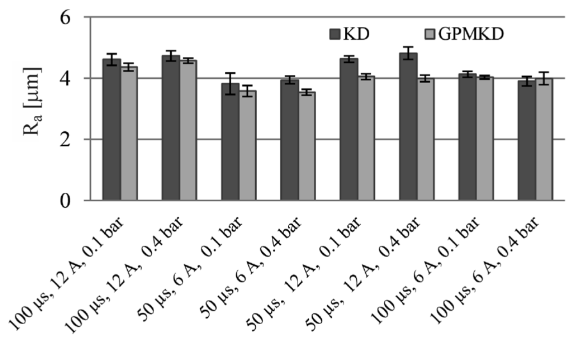

Fig. 5. *Effect of* GPMKD *on* R_a

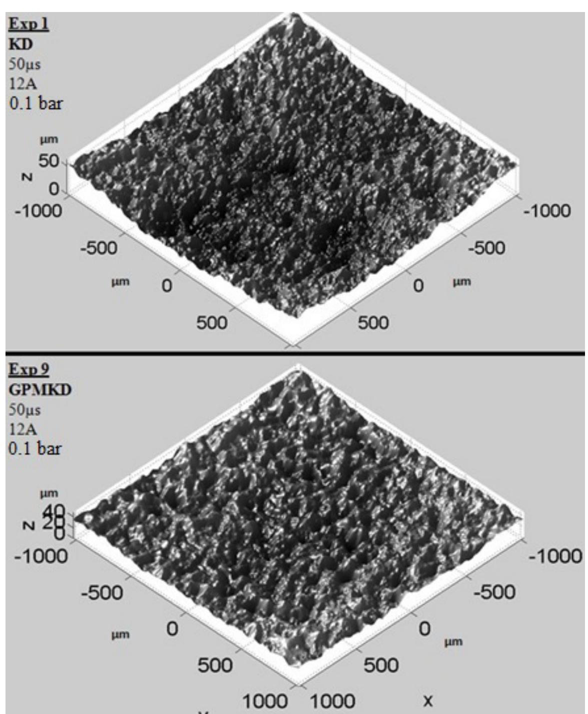

Fig. 6. *The 3D topographic views of the workpiece surfaces (Exp. 1 and 9)*

The average workpiece surface peak-to-valley heights of the KD experiments (~50 μm in Exp. 1 (Fig.

6a)) were decreased in GPMKD cases (~40 µm in Exp. 9 (Fig. 6b)). Uneven distribution of peaks and valleys was also observed in KD experiments due to frequent occurrences of undesirable arcs at the same spot. Magnified surface topography photographs revealed uniformly distributed short and round top peaks due to the uniform distribution of discharge energy in the gap in the GPMKD experiments. The surface topographies shown in Fig. 7 were formed by half of the energy discharges of Fig. 6 resulting in smaller craters and shorter peaks. In the GPMKD experiments, the z axis average height is decreased from ~40 µm to ~20 µm with respect to KD experiments. Roughness measurements revealed 4.8 % to 13.4 % reduction in $R_{Z(DIN)}$ values in GPMKD cases (Table 4). This reduction also verified the formation of shorter peaks (smaller peak-to-valley heights) through the use of the GPMKD.

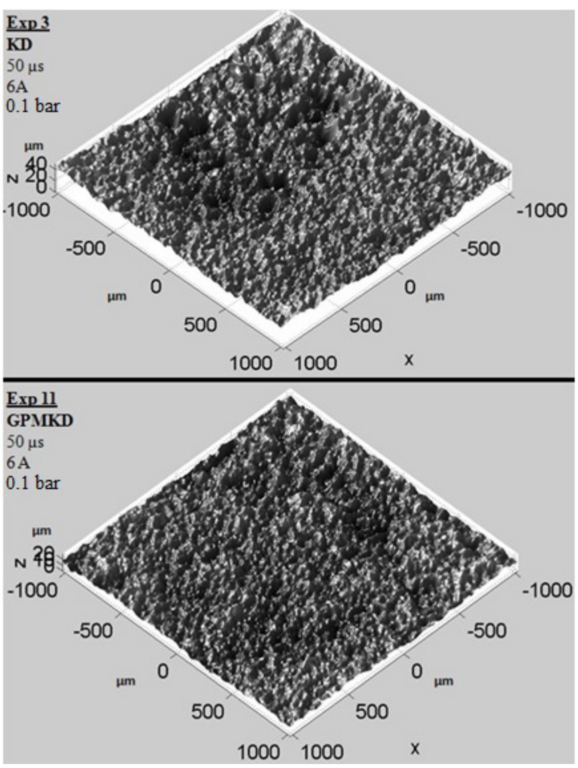

Fig. 7. *The 3D topographic views of the workpiece surfaces (Exp. 3 and 11)*

Table 4. $R_{z(DIN)}$ *measurements*

KD		GPMKD		Diff. [%]
Exp. no	$R_{z(DIN)}$ [µm]	Exp. no	$R_{z(DIN)}$ [µm]	
1	23.4	9	21.2	9.4
3	23.0	11	19.9	13.4
5	24.8	13	22.5	9.2
6	25.2	14	24.0	4.8

3.3 Effect of GPMKD on EWR and RW

Although it can be observed that EWR and RW increased with increasing values of P_d for both KD and GPMKD experiments, the EWR and RW values show significant variations depending on the values of t_s and i_d. The EWR and RW were decreased noticeably with increasing t_s (Figs. 8 and 9). The decrease in RW with increasing t_s was an expected result since the MRR increases and EWR decreases with increasing t_s. It was found that the i_d was the most significant machining parameter affecting machining performance outputs of Ti-6Al-4V. At high i_d settings, more electric current (energy) passing through the gap results in a large amount of workpiece and electrode material removal by melting and evaporation [11] and [22]. Due to this fact, the increased i_d resulted in higher R_a (Fig. 5), EWR (Fig. 8) and RW (Fig. 9).

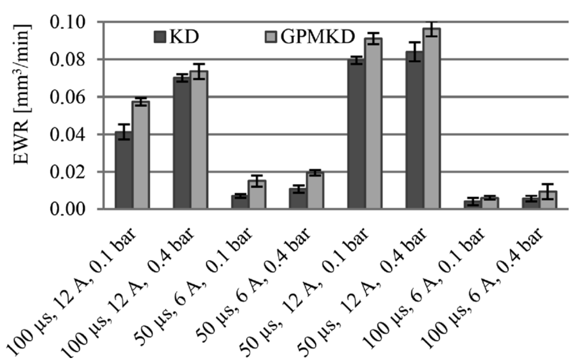

Fig. 8. *Effect of* GPMKD *on* EWR

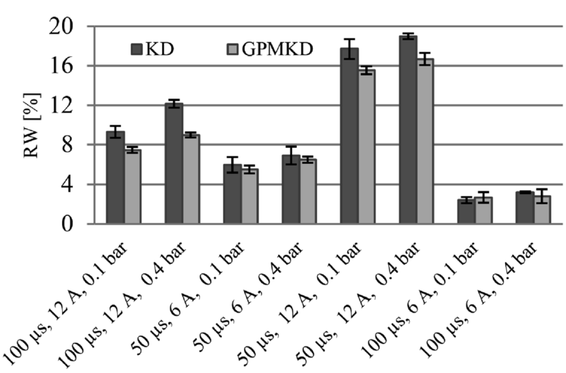

Fig. 9. *Effect of* GPMKD *on* RW

Slight increases in the EWR values were observed in the GPMKD compared to KD experiments (Fig. 8). This was attributed to big crater formations with the increasing electrical conductivity of the dielectric liquid in the GPMKD cases. In this study, a 4 % to 72 % increase in EWR was observed by using GPMKD for the tested machining settings. In machining of

Ti-6Al-4V with Al or SiC powder mixed kerosene or deionized water, a 150 % to 200 % [16], 57 % [17] and 105 % to 175 % [18] increase in EWR have been reported. Therefore, the increase in EWR observed in this study could be considered to be in reasonable agreement with other studies. On the other hand, a 15 % decrease in EWR was reported in machining of a mild steel workpiece with GPMKD at a low pulse discharge energy [7].

Fig. 9 clearly highlights the contribution of GPMKD use on the reduction of RW (7.7 % to 26 %). This is an important measure of long tool electrode life and economical machining.

3.4 Comparison of ED Machinability of AISI 1040 and Ti 6Al-4V Workpieces

The MRR of Ti-6Al-4V was 14.9 to 18.6 times slower than that of AISI 1040 for the KD experiments. Although the MRR was improved greatly by GPMKD use, the MRR of Ti-6Al-4V was still 11.9 to 13 times slower than that of AISI 1040 (Fig. 10). The RW values obtained in Ti-6Al-4V were 0.4 to 2.4 times higher than AISI 1040 in KD experiments. The GPMKD use reduced these values by ~20 % (Fig. 11). The lower electrical resistance and higher heat conductivity of the AISI 1040 than the Ti-6Al-4V led to larger diameter and deeper crater formations (evident from microscopic examinations) causing higher R_a values (Fig. 12).

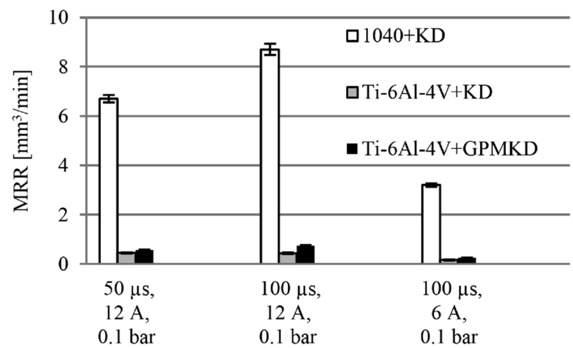

Fig. 10. *Comparison of* MRR *values of AISI 1040 and Ti-6Al-4V*

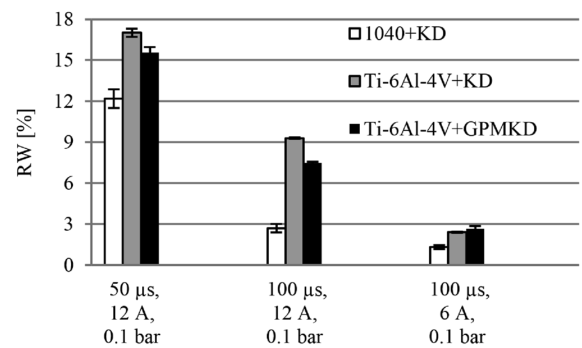

Fig. 11. *Comparison of* RW *values of AISI 1040 and Ti-6Al-4V*

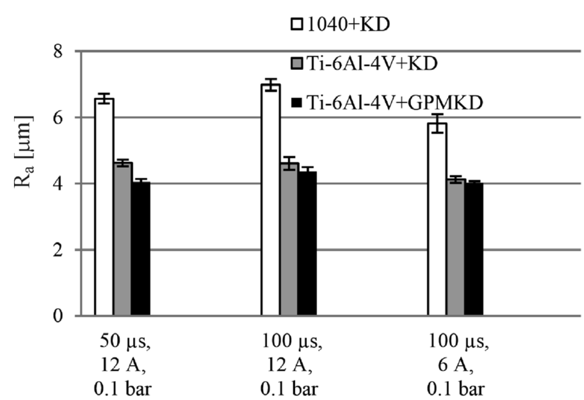

Fig. 12. *Comparison of* R_a *values of AISI 1040 and Ti-6Al-4V*

4 CONCLUSION

This study is the first significant effort to use a graphite powder mixed dielectric to improve ED machining performance of the Ti-6Al-4V alloy in an EDM die sinking operation. The experimental results allow us to draw the following conclusions:

1) The increasing dielectric flushing pressure (P_d) improved the MRR significantly and increased the tool electrode wear rate (EWR) slightly for both the kerosene dielectric (KD) and the graphite powder mixed kerosene dielectric GPMKD cases. The R_a wasn't affected noticeably by the variation in P_d. Increasing t_s increased the MRR and decreased the EWR for KD and GPMKD. No changes in R_a were observed with the variation in t_s.
2) The machining was very stable and machined surfaces were free of carbon contamination in the GPMKD experiments, especially at high P_d settings.
3) The GPMKD improved the MRR, R_a and RW of Ti-6Al-4V workpiece. The 3D surface topography of the machined surfaces revealed that the GPMKD use resulted in lower peak-to-valley heights than the KD experiments.
4) Although the use of GPMKD improved the MRR of the Ti-6Al-4V significantly, the MRR values with respect to the AISI 1040 steel workpiece were still low. However, much better R_a values in Ti-6Al-4V than in AISI 1040 were obtained with the use of KD and GPMKD.

Graphite powder is at least 70 % cheaper than other metallic and non-metallic powders used in the literature and is, thus, economically highly attractive. Moreover, the lower density of the graphite powder than the other powders provides a more homogenous suspension of the powder, which provides a stable ED machining regime. We also emphasize that the proposed graphite powder addition to the dielectric can be readily adapted to EDM die sinking and EDM drilling applications of Ti-6Al-4V in the aerospace industry considering the observed improvements in machining performance and lower costs.

5 NOMENCLATURE

MRR	Material removal rate [mm³/min]
EWR	Tool electrode wear rate [mm³/min]
RW	Relative wear (EWR/MRR) [%]
R_a	Average surface roughness [µm]
$R_{z(DIN)}$	Average of the highest peak to valley measurements found for each cut-off length [µm]
t_s	Pulse time (pulse on time) [µs]
t_p	Pause time (pulse off time) [µs]
i_d	Discharge current [A]
C_p	Powder concentration [g/l]
P_d	Dielectric flushing pressure [bar]

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