Jurnal
Teknologi

Full paper

Surface Study in a Non-conventional (Electrical Discharge Machining) Process for Grade 6 Titanium Material

Md. Ashikur Rahman Khan[a*], M. M. Rahman[b]

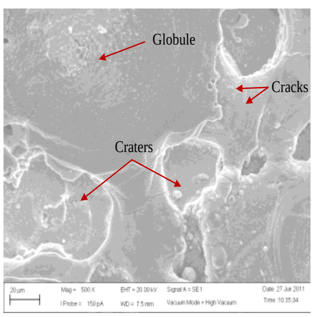
[a]Department of Information and Communication Technology, Noakhali Science and Technology University, Sonapur, Noakhali-3814, Bangladesh
[b]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

*Corresponding author: ashik.nstu@yaoo.com

Article history

Received :16 April 2013
Received in revised form :
26 February 2014
Accepted :15 March 2014

Graphical abstract



Microstructure of the machined specimen

Abstract

Electrical discharge machining (EDM) produces complex shapes and permits high-precision machining of any hard or difficult-to-cut materials. The performance characteristics such as surface roughness and microstructure of the machined face are influenced by numerous parameters. The selection of parameters becomes complicated. Thus, the surface roughness (R_a) and microstructure of the machined surface in EDM on Grade 6 titanium alloy are studied is this study. The experimental work is performed using copper as electrode material. The polarity of the electrode is maintained as negative. The process parameters taken into account in this study are peak current (I_p), pulse-on time (T_{on}), pulse-off time (T_{off}), and servo-voltage (S_v). A smooth surface finish is found at low pulse current, small on-time and high off-time. The servo-voltage affects the roughness diversely however, a finish surface is found at 80 V S_v. Craters, cracks and globules of debris are appeared in the microstructure of the machined part. The size and degree of craters as well as cracks increase with increasing in energy level. Low discharge energy yields an even surface. This approach helps in selecting proper process parameters resulting in economic EDM machining.

Keywords: Surface structure; grade 6 Ti; negative polarity; copper electrode; discharge energy

Abstrak

Pemesinan pelepasan elektrik (EDM) menghasilkan bentuk yang kompleks dan permit pemesinan kepersisan tinggi daripada mana-mana bahan-bahan keras atau sukar untuk dipotong. Ciri-ciri prestasi seperti kekasaran permukaan dan mikrostruktur muka dimesin dipengaruhi oleh parameter banyak. Pemilihan parameter menjadi rumit. Oleh itu, kekasaran permukaan (Ra) dan mikrostruktur permukaan dimesin dalam EDM pada Gred 6 aloi titanium dikaji ialah kajian ini. Kerja-kerja eksperimen dilakukan dengan menggunakan tembaga sebagai bahan elektrod. Kekutuban elektrod dikekalkan sebagai negatif. Parameter proses diambil kira dalam kajian ini adalah semasa puncak (IP), nadi pada masa (Ton), masa nadi-off (bangsawan), dan servo-voltan (Sv). A kemasan permukaan licin ditemui di nadi semasa yang rendah, kecil pada masa dan tinggi dari masa. The servo voltan kesan kekasaran diversely bagaimanapun, kemasan permukaan terdapat di 80 V Sv. Kawah, retak dan globules serpihan yang muncul dalam mikrostruktur bahagian dimesin. Saiz dan tahap kawah serta retak peningkatan dengan peningkatan dalam tahap tenaga. Tenaga pelepasan rendah hasil yang lebih permukaan. Pendekatan ini membantu dalam memilih parameter proses yang betul menyebabkan ekonomi EDM pemesinan.

Kata kunci: Struktur permukaan; gred 6 Ti; kekutuban negatif; elektrod tembaga, tenaga pelepasan

1.0 INTRODUCTION

At this time, titanium is one of the most important materials in industry[1]. Titanium has found its position in many industries owing to its unique characteristics which make it preferable to other materials such as aluminium, steels, and super alloys. Titanium is an allotropic element; it exists in more than one crystallographic structure[2]. Grade 6 (Ti-5Al-2.5Sn) titanium alloy is a suitable and important titanium alloy, although there are distinct types of titanium alloys such as Ti-6Al-4V (Grade 5), Ti-6Al-6V-2Sn (AMS 49812), Ti-15V-3Cr-3Al-3Sn (ASTM B265), Ti-5Al-5V-5Mo-3Cr (Ti-5553), Ti-3Al-2.5V (Grade 9), Ti-10V-2Fe-3Al (AMS 4984), and Ti-5Al-2.5Sn (Grade 6) alloy. Grade 6 titanium alloy is not toxic to the environment like other titanium alloys. It is used in airframes and jet engines due to its good weldability, stability, and strength at elevated temperatures[3]. Ti-5Al-2.5Sn is also used for manufacturing steam turbine blades, autoclaves and other process equipment vessels, cryogenic vessels, aircraft engines, compressor blades, missile fuel tanks and structural parts, airframe and jet-engine parts, welded stator assemblies, and hollow compressor blades[4].

In spite of the increased utility of titanium alloys, the capability to produce parts products with high productivity and superior quality becomes challenging[5, 6]. It accrued a key problem in machining using conventional techniques[7, 8]. On the other hand, a non-conventional technique, electrical discharge machining can machine titanium and titanium alloy effectively. Electrical discharge machining is a thermo-electrical material removal technique, in which electrode (tool) shape is reproduced mirror wise into a workpice material, with the shape of the electrode defining the area in which the spark erosion will occur. In EDM, there are no standard technologies readily available for setting the machining parameters to achieve the desired machining performance of titanium alloys, especially Grade 6.

A small number of research works on EDM of titanium alloys has been published. Most of these studies, which are being stated here, are carried out with regard to Grade 5 (Ti-6Al-4V) titanium alloy. Chen *et al*. studied the electrical discharge machining characteristics on Grade 5 material altering the dielectric fluid[9]. They exercised copper as electrode material, and considered discharge current and pulse-on time as process variables. Hascalik and Caydas investigated the machining characteristics using dissimilar electrodes, namely graphite, copper and aluminium[10]. They considered two process parameters as discharge current and pulse-on time. Fonda *et al*. explored the effect of thermal and electrical properties of the workpiece material Grade 5 titanium alloy on EDM productivity using copper as electrode and duty factor as process material[11]. Besides, a few researchers studied the modelling for correlating the EDM process parameters and responses[12, 13]. Current, voltage and machining time were selected as process parameters, and copper was used as electrode material in these studies. On the other hand, Kao *et al*. optimized the process variables such as voltage, current, pulse-on time, pulse-off time and duty factor[14]. Here, they utilized copper electrode material for EDM on Grade 5 titanium alloy.

The literature review shows that the study with regard to surface characteristics in EDM on Grade 6 titanium alloy has not been carried out yet, although the EDM performance characteristics have been studied for various materials including Grade 5 titanium alloy. Then again, the EDM performance characteristics are not similar for all workpiece-electrode material combination. In this viewpoint, an effort has been made to study the surface roughness (R_a) and microstructure of the machined surface in electrical discharge machining on Grade 6 titanium alloy. The microstructure of the surface are analysed for different discharge energies. In this research work, peak current, pulse-on time, pulse-off time, and servo-voltage are taken into consideration as process variables. Experiments are carried out varying these all process variables for copper electrode with negative polarity.

■2.0 RESEARCH METHODOLOGY

2.1 Materials

Grade 6 (Ti-5Al-2.5Sn) titanium alloy has been selected as workpiece material in this study. The chemical compositions of Grade 6 titanium alloy are listed in Table 1[15]. This material is available commercially in many forms. The Grade 6 titanium alloy has excellent mechanical properties and maintains its strength at temperatures up to 600 ºC. Typically, copper and graphite electrodes can be used for the same EDM jobs, and these two electrodes are used extensively by the majority of EDM users in Europe, Asia and the United States of America[16]. In the present research work, copper is chosen as electrode materials.

Table 1 Chemical composition of Grade 6 titanium alloy

Element	Al	V	Mo	Sn	Fe
wt %	5.1	-	-	2.6	0.15
	C	N	H	O	Ti
	0.02	0.01	0.001	0.11	Balance

2.2 EDM Process Parameters

In EDM, the removal of material is based upon the electro discharge erosion (EDE) effect of electric sparks occurring between two electrodes that are separated by a dielectric liquid. Metal removal takes place as a result of the generation of extremely high temperatures generated by the high-intensity discharges that melt and evaporate the two electrodes. Temperatures of about 8000 to 12,000 ^{0}C and heat fluxes up to 1017 W/m^2 are attained[17]. With a very short duration spark of typically between 0.1 to 2000 µs the temperature of the electrodes can be raised locally to more than their normal boiling points. A series of voltage pulses of magnitude about 20 to 120 V and frequency on the order of 5 kHz is applied between the two electrodes, which are separated by a small gap, typically 0.01 to 0.5 mm. Electrical discharge machining parameters are separated into two groups: non-electrical parameters and electrical parameters. Non-electrical parameters are as injection flushing pressure, rotational speed of electrode, and so forth. Electrical parameters are as peak current, polarity, pulse duration, and power supply voltage.

The peak current, pulse-on time, pulse-off time, and servo-voltage were selected as the process variables for the present research based on literature review as well as the preliminary experiment. In EDM, the peak current supplied by the generator of the EDM machine is the most important machining parameter. Throughout the pulse-on time, the current increases until it reaches the peak current which is a pre-set value. In the electrical discharge process, every pulse comprises on time and off time, and these are expressed in microseconds (µs). Discharge pulse-on time is the time of continuous discharge (current)[18]. Pulse-off time is the duration of time (µs) between two successive pulse durations. Pulse-off time can be defined as the period between the ending of discharge and the beginning of the next discharge[18]. Servo-voltage specifies a reference voltage for servo motions to keep the gap-voltage constant[19] and can be fixed by the technician. In the EDM process, the servo motion is controlled in accordance with gap-voltage fluctuation relative to servo-voltage.

Surface roughness is the most important and frequently used parameter and accordingly, it is chosen as the performance parameter of the EDM experiment. In addition, the microstructure of the machined surface was set as objective function in this study. Generally, the surface roughness is measured in terms of arithmetic mean (R_a) which according to the ISO 4287:1997 is defined as the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement[20]. In this study, the arithmetic average (R_a) is used for assessment of surface roughness of the machined surface.

2.3 Experimentation

Experimentation was performed retaining negative polarity of the copper electrode. In negative polarity, the workpiece is connected to the positive terminal and the tool is connected to the negative terminal of the source. Experiments are carried out varying the peak current, pulse-on time, pulse-off time, and servo-voltage within the range as presented in Table 2.

Table 2 The process parameters and their ranges

Process parameters	Range
I_p (A)	1–29
T_{on} (µs)	10–350
T_{off} (µs)	60–300
S_v (V)	75–115

The value of surface roughness (R_a) of the machined part, grade 6 titanium alloy was assessed using the Perthometer S2 from Mahr, Germany. Microstructure analysis was carried out by scanning electronic microscopy (SEM) to observe the surface microstructure of selected specimens. The experiments mainly varied the energy intensity (peak current × pulse-on time), since the surface attribute is mainly associated with pulse energy (pulse current and/or pulse-on time) as shown in Table 3[21]. The specimens were got ready after experiments. During the experiment, the value of pulse-off time and servo-voltage were kept as constant. Then, the microstructure of the workpiece surface was investigated using SEM model-EVO 50 from Zeiss, Germany. All specimens were analysed with regard to negative polarity of the copper electrode. SEM micrographs are accomplished from the machined surface at 500× magnifications size.

Table 3 Set of designed experiments for SEM viewing

Sl no.	Peak current (A) × Pulse-on time (µs)
1	15 × 180
2	29 × 320
3	2 × 95

■3.0 SURFACE ROUGHNESS OF THE WORKPIECE

The effect of each of the process parameters—peak current, pulse-on time, pulse-off time, and servo-voltage—on the surface roughness is analysed following experimentation. The results obtained through experimentation and analyses are discussed here. The effect of the process parameters are presented in Figure 1–4. Figure 1 shows the effect of peak current on the surface roughness. It is apparent from Figure 1 that the R_a increases with increasing peak current. As pulse current increases, discharges strike the surfaces more strongly, hence a great quantity of material is melted resulting in more craters during EDM. Ultimately, the surface finish becomes rougher when the peak current increases. On the other hand, low discharge current creates small craters resulting a smooth surface finish. Thus, the increase of peak current increases R_a, and low ampere produces a lower R_a.

The effects of pulse-on time on the workpiece surface roughness are presented in Figure 2. It is perceived that the R_a increases upon increasing the pulse-on time. However, it is observed that initially the R_a increases until a specific value and then does not vary significantly when the pulse-on time increases. The crater development and material removal are proportional to the amount of applied energy during on-time, which is a function of I_p and T_{on}. This discharge energy is directly connected with the pulse-on time; accordingly a long pulse-on time creates more craters and erodes more material Therefore, a long T_{on} generates a rougher surface. The low R_a of the EDM machined surface is attained at low T_{on}. The energy density is reduced within the discharge spot upon extending the pulse-on time, and a tenuous discharge occurs as a result. The amount of workpiece material removed at a single pulse is decreased, and the surface topography turns into more even. Thus, the degree of increasing of R_a tends to decline under longer pulse duration.

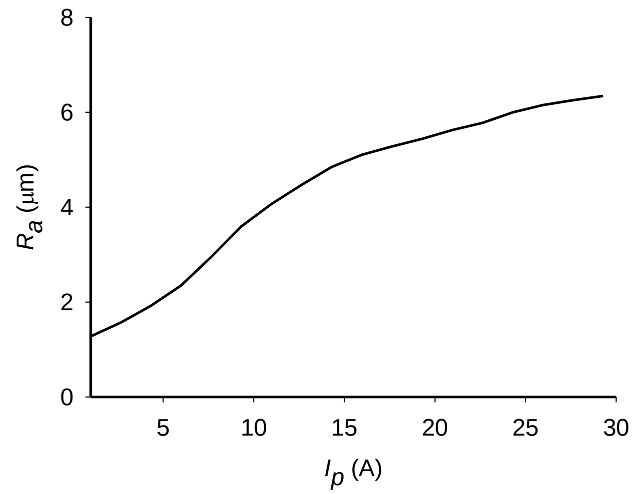


Figure 1 Surface roughness for varied pulse-on time

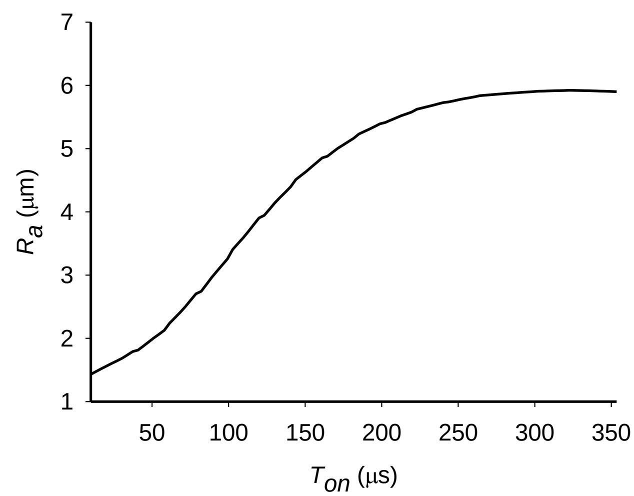


Figure 2 Surface roughness for varied pulse-on time

The effect of pulse-off time on R_a is shown in Figure 3. As can be seen from the figure, the increase of T_{off} causes a falling tendency of the surface roughness graph. If the T_{off} is too short, there is not enough time to clear the disintegrated elements from the gap between the electrode and the workpiece. The too short T_{off} induces an unstable spark discharge because of insufficient insulation recovery[18]. Thus, the surface roughness trends to decrease whilst the T_{off} time increases.

The effect of the servo-voltage on the R_a is shown in Figure 4. The diverse effect of S_v on R_a is apparent in this figure. The increase of S_v primarily decreases R_a until certain value of S_v then increases R_a, and finally results in a decreasing trend of R_a. Although the diverse effect is evident, the increasing trend of R_a with the increase of S_v is more dominant. Lowest surface roughness is found when the S_v is 80 V. The S_v controls the spark gap during the process of electrical discharge machining, and the increase of S_v increases the spark gap. At the high S_v, the electrode is not able to advance longer towards the workpiece. Accordingly, the material removal as well as the R_a supposed to be decreased whilst the S_v increases. In contrast, here the diverse effect of S_v as well as the increasing trend of R_a with the increase of S_v is found due to the negative polarity of the copper electrode and unstable machining. An extended discharge waveform is established at the pulse-off time when the polarity is negative. This is owing to many particles of copper electrodes drop and accumulate to the machined surfaces, interfering with the discharge proceeding. As a result, the discharge state becomes rather unstable. Thus, the machining causes higher R_a.

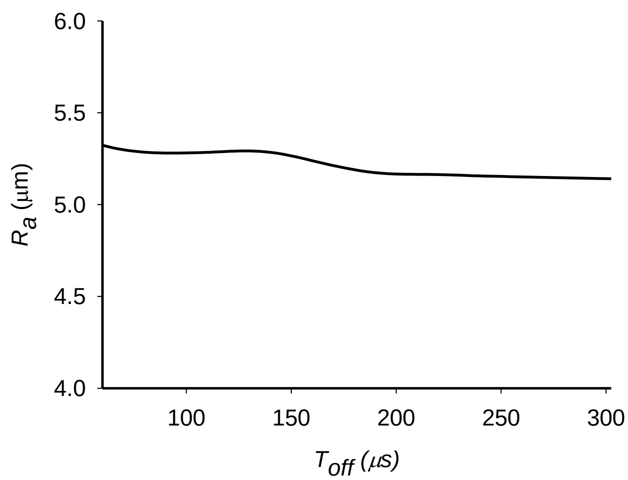


Figure 3 Surface roughness for varied pulse-off time

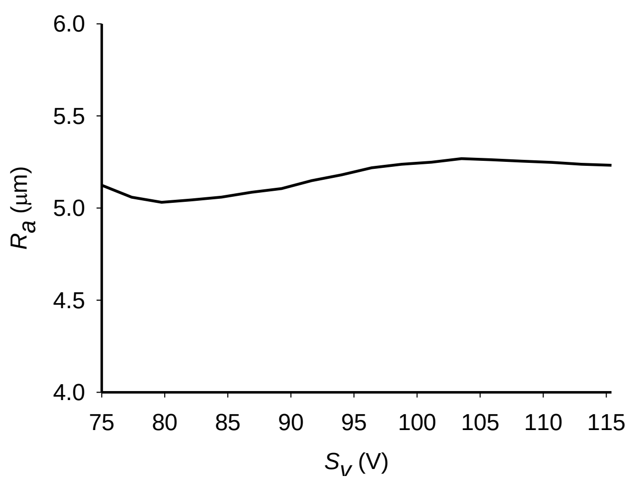


Figure 4 Surface roughness for varied servo-voltage

■4.0 MICROSTRUCTURE OF THE WORKPIECE

The microstructure of the workpiece surface of a number of samples is studied using scanning electronic microscopy to analyse the surface microstructure of the machined face. The analysis is performed for distinct pulse energy such as 2 A × 95 µs, 15 A × 180 µs, and 29 A × 320 µs. Figures 5–7 shows the microstructure of the specimen machined for distinct pulse energy. Scanning electronic microscopic images have craters, cracks, and globules of debris on the surface.

The machined face contains few craters but most of the machined plane is covered with globules as shown in Figure 5. The surface topography looks like liquid metal has been poured and resolidified. Here, the electrode retains negative polarity (cathode) while the workpiece possesses positive polarity (anode). The atoms from the anode are obstructed by the electrons coming from the electrode. Some of the atoms are ionized, and the remainder strike the electrode with greater energy intensity resulting in electrode erosion. A portion of the melted electrode accumulates on the workpiece surface, producing globules of debris. Therefore, the SEM micrograph displays a greater number of globules. The spark occurring through the high-temperature plasma erodes and vaporizes the material from the surface, and ultimately craters are produced. The crater size relates with the pulse current as well as the pulse energy, and low pulse energy results in few craters as shown in Figure 5. The microstructure shows the presence of cracks due to rapid cooling of the recast layer. Many surface imperfections in the recast layer produced by the EDM process initiate cracking. The cracks are in the form of micro-cracks. In another word, lower discharge energy produces micro-cracks. Thus, low discharge energy creates small and shallow craters, micro-cracks, and globules.

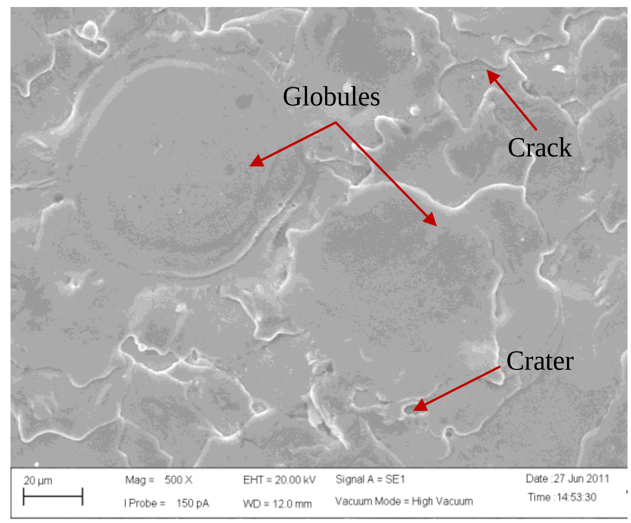


Figure 5 Microstructure of the machined specimen for $I_p \times T_{on}$ = 2 A × 95 µs

According to the SEM images in Figure 5–7, the surface characteristics (crater, crack and globule) are distorted on account of discharge energy. The size and depth of the discharge craters increase as the discharge energy level increases. The increase of discharge current and pulse-on time increases the discharge energy. The large discharge energy causes violent sparks and impulsive force, which strike the surface. The large impulsive force advances in the spark gap. The rate of melting and vaporization is increased, resulting in greater material erosion. This results in larger and deeper craters on the machined surface. Therefore, high discharge energy produces deeper and wider craters, generating a rougher surface. As the discharge energy increases the amount of globules decreases. There are two reasons— one is high discharge energy causes lower globule formation due to lower electrode erosion, the other one is high discharge energy causes a large impulsive force, which can remove more debris from the machining gap. Thus, the surface topography with high discharge energy presents a smaller number of globules.

It is appeared from the Figure 5–7 that the increasing in pulse energy results higher degree of crack. The increase in pulse-on time increases the residual stress. A larger amount of heat energy penetrates into the interior of the material at long pulse-on time. The temperature of the machined surface reaches the melting point readily. The molten material resolidifies following rapid cooling (quenching) by the dielectric fluid, subsequently the degree of crack increases. Thus, the high discharge energy produces a greater degree of cracks with wide openings.

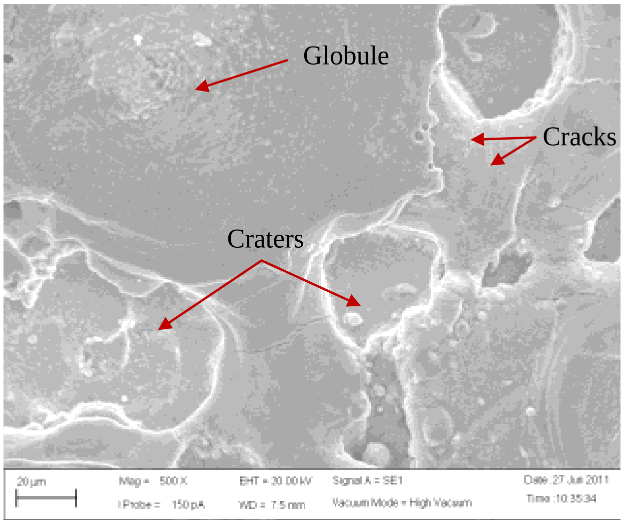


Figure 6 Microstructure of the machined specimen for $I_p \times T_{on}$ = 15 A × 180 µs

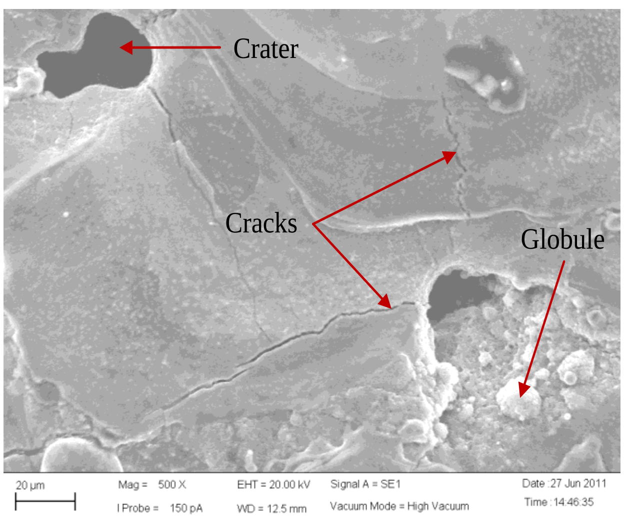


Figure 7 Microstructure of the machined specimen for $I_p \times T_{on}$ = 29 A × 320 µs

■5.0 CONCLUSION

An extensive experimental study has been conducted to investigate the effect of the machining parameters on R_a and surface structure in EDM of Ti-5Al-2.5Sn titanium alloy with negative polarity of copper electrode. The machining parameters are I_p, T_{on}, T_{off}, and S_v. The following conclusions can be drawn from the study.

Surface roughness increase with peak current and pulse-on time however, decreases with pulse-off time. The degree of increasing of R_a tends to decline under longer on-time. In this study, the diverse effect of servo-voltage is appeared. Again, 80 V S_v produces lowest surface roughness. The increase of S_v primarily decreases R_a until certain value of S_v then increases R_a, and finally results in a decreasing trend of R_a. Although the diverse effect is evident, the increasing trend of R_a with the increase of S_v is more dominant. Low pulse current, small on-time and high off-time yields a smooth surface finish.

Scanning electronic microscopic micrograph displays craters, cracks, and globules of debris on the machined. A greater number of globules are found, where the surface topography is looked like liquid metal has been poured and resolidified at low discharge energy. Low discharge energy creates small craters, micro-cracks, and globules. The size and degree of craters as well as cracks increase as the discharge energy level increases. It is found that high discharge energy produces rougher surface. The surface structure with high discharge energy presents a smaller number of globules. Low discharge energy furnishes an even surface of the machined part.

This study helps in selecting proper parameters for EDM machining as well as cost estimation. This research work facilitates an economic machining saving the time.

Acknowledgement

The authors would like to be thankful to the Universiti Malaysia Pahang, Malaysia for their support.

References

[1] X. Liu, P. K. Chu, C. Din. 2004. *Mater. Sci. Eng. R*. 47: 49–121.
[2] M. J. Jr. Donachie, 2000. *Titanium: A Technical Guide*. 2nd ed. USA: ASM International.
[3] M. M. Rahman, M. A. R. Khan, K. Kadirgama, M. M. Noor, R. A. Bakar, 2010. *Adv. Control, Chem. Eng. Civil Eng. Mech. Eng.* WSEAS. 34–37.
[4] M. A. R. Khan, M. M. Rahman, K. Kadirgama, A. R. Ismail. 2012. *J. Teknol*. 59: 57–61.
[5] M. M. Rahman, M. A. R. Khan, M. M. Noor, K. Kadirgama, R. A. Bakar. 2011. *Adv. Mater. Res*. 213: 402–408.
[6] M. A. R. Khan, M. M. Rahman, K. Kadirgama, M. A. Maleque, R. A. Bakar. 2011. *World Acad. of Sci. Eng. Technol*. 74: 121–125.
[7] M. A .R. Khan, M. M. Rahman, K. Kadirgama. 2012. *Adv. Sci. Lett*. 14: 879–884.
[8] M. A. R. Khan, M. M. Rahman, K. Kadirgama, R. A. Bakar. 2012. *Energy Educ. Sci. Techn. Part A: Energy Sci. Res*. 29(2): 1025–1038.
[9] S. L. Chen, B. H. Yan, F. Y. Huang. 1999. *J. Mater. Process. Technol.* 87: 107–111.
[10] A. Hascalik, U. Caydas. 2007. *Appl. Surface Sci.* 253: 9007–9016.
[11] P. Fonda, Z. Wang, K. Yamazaki, Y. Akutsu. 2008. *J. Mater. Process. Technol.* 202: 583–589.
[12] G. K. M. Rao, G. R. Janardhana, D. H. Rao, M. S. Rao. 2008. *ARPN J. Eng. Applied Sciences*. 3(1): 19–30.
[13] G. K. M. Rao, G. R. Rangajanardhana, D. H. Rao, M. S. Rao. 2009. *J. Mater. Process. Technol.* 209: 1512–1520.
[14] J. Y. Kao, C. C. Tsao, S. S. Wang, C. Y. Hsu. 2010. *Int. J. Adv. Manuf. Technol.* 47: 395–402.
[15] D. R. Swalla, R. W. Neu. 2006. *Tribology Int.* 39: 1016–1027.
[16] F. L. Amorim, W. L. Weingaertner, 2007. *J. Braz. Soc. Mech. Sci. Eng.* 29(4): 367–371.
[17] H. El-Hofy. 2005. *Advance Machining Processes.* Production Engineering Department Alexandria University. Egypt.
[18] K. L. Wu, B. H. Yan, J. W. Lee, C. G. Ding. 2009. *J. Mater. Process. Technol.* 209: 3783–3789.
[19] M. Kunieda, B. Lauwers, K. P. Rajurkar, B. M. Schumacher. 2005. *CIRP Annals – Manuf. Technol.* 54(2): 64–87.
[20] K. L. Wu, B. H. Yan, F. Y. Huang, S. C. Chen. 2005. *Int. J. Mach. Tools & Manuf.* 45: 1195–1201.
[21] H. Ramasawmy, L. Blunt, K. P. Rajurkar. 2005. *Precision Eng.* 29: 479–490.