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Analysis of microlayer defects of a functionally graded titanium alloy by electrical discharge machining

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Abstract

This paper reports on the surface characteristics of a functionally graded Titanium (Ti-6Al-4V) alloy during Electrical Discharge Machining (EDM). The electrical discharge input parameters employed for this work are current (I), on-time (Ton), off-time (Toff) and spark gap voltage (V). The electrode used for EDM of the titanium workpieces is an electrolytic copper electrode. The two machining processes employed are at room temperature and sub-zero temperature using liquid nitrogen at -160^{0}C as electrode coolant during the process. EDM machining was designed for all the input parameters and the materials machined with three different currents, i.e., 4.5A, 5.5A and 7.5A, while the workpieces were examined for microlayer defects using scanning electron microscopy (SEM). The result showed an average micro-layer thickness of 24.47 µm with current of 7.5A when machined at -160^{0}C. Also an increase in crack formation with the highest current of 7.5A for the surfaces machined at subzero temperature was recorded for both the workpieces and electrode materials.

Keywords: Defects, Electrode, Input parameters, Microlayer, Subzero temperature

1. Introduction

Electrical Discharge Machining (EDM) removes material from workpiece by the action of electrical discharges (ED) of short duration between two electrodes (i.e., the workpiece and tool) [1]. Melting of workpiece in electrical discharge (ED) machining is usually achieved by high temperature electrical discharges, and the molten materials are flushed away by a hydrocarbon dielectric fluid [2]. The developments in EDM processes have advanced due to the ever demanding application of the process and the challenges faced by manufacturing industries, resulting from the development and processing of hard and difficult-to-machine materials.

EDM is a thermal material removal process that finds its application in the production of tools, dies, molds, intricate and delicate workpieces, as well as production of hard-to-machine materials such as titanium alloys, inconel, stainless steels, tool steels, composites, ceramics, super alloys, hastalloy, carbides, and heat resistant steels [2-3]. Further application of EDM processes also is found in the production of sporting goods, medical instruments, optical and dental materials [4]. EDM technology is being used in tool, die and mould industries, for machining heat treated tool steels and advanced materials requiring sophisticated applications, complex shapes and equipment requiring high surface precision [5-6].

This research focuses on EDM machining of a titanium alloy because titanium has a wide range of applications. Ordinarily, titanium alloys are hard-to-machine materials because of their high strength at elevated temperatures during machining, hence the choice of EDM process. During EDM machining, electrode (tool) wear is a major problem. According to Ozgedik and Cogun [7], the contribution of tool electrode costs to the total the machining costs is more than 70%. When tool electrode wear occurs during EDM, the required geometric dimensions and form of the electrode are not reproduced on the workpiece, thereby giving a poor configuration to the machined part. To minimize the effect of electrode wear on the machined part, it is necessary to cool the electrode by machining at a temperature of -160^{o}C to reduce the wear that is taking place on electrode during EDM machining.

However, since there is a rapid and high induced temperature surge on the electrode and workpiece during the EDM machining process, the electrodes and workpiece melt and vapourize [8]. The volume of the electrode and workpiece melted and vapourized, as well as the consequences of incomplete flushing of the molten materials (electrode and workpiece) from the spark gap, results in solidification of molten materials from both the electrode and workpiece and their deposition as a micro-layer defect during cooling. Sudden cooling of the electrodes by a hydrocarbon

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dielectric fluid during machining results in micro-layer defects (micro cracks) on the electrically discharged machined surface [9-12]. These are some of the major problems with EDM processes and hence there is a need to carry out analysis of microlayer defects of titanium alloys produced during the electrical discharge machining process. One of the ways of addressing these issues is to establish machining conditions that minimize such problems. Successive impinging of discharges on workpiece causes an increased temperature of the workpiece that results in induced thermal stresses within the material [13]. Residual stresses are induced within the recast layer due to rapid cooling. When the stresses exceed the material's ultimate tensile strength, cracking of the surface takes place [10-11, 14].

Some researchers have reported on recast layer characteristics. Yildiz et al. [15] modeled and analyzed white layer thickness formation in electro discharge machining of beryllium-copper alloys using an image processing technique. They concluded that a second order difference equation model was statistically adequate for modeling and forecasting the white layer thickness profiles. The work of [16] dealt with metallurgical alterations on the surface of steel cavities machined by EDM. They reported that metallurgical alterations have a significant influence on the mechanical properties of an electrical discharge machined surface and on the reliability of the machined parts. In a related work of [17], modeling of white layer formation in electric discharge machining (EDM) was done by incorporating massive random discharge characteristics. In their report, it was concluded that a FEA model with massive random discharging characteristics could simulate the solid white layer formation and heat affected zone (HAZ) formation. [18] reported that surface residual stresses increased with structural non-homogeneities in the white layer. He stated that no clear consequence was observed in residual stress distribution under the white layer. Conclusively, the work of [19] shows that the use of an oil dielectric fluid increased the carbon content in the white layer, while a water dielectric material caused decarbonisation of the white layer.

In view of the aforementioned facts, there is a need to carry out analysis of microlayer defects of functionally graded titanium alloy by electrical discharge machining. However, available literature reveals that many researchers have worked on micro-layer defects such as recast layers and microcracks. These studies rarely reported on defects with a tool electrode at a subzero temperature of -160^{0}C during EDM machining.

2. Equipment and experimentation

The machine used in this study was an EDM EX22 Mitsubishi-C11E FP60E, (Japan) with EDM 3033 hydrocarbon dielectric oil as a flushing fluid to clean the spark gap during the process. A downpour emission system of flushing with a pressure of 15 psi was employed. The workpiece in the study was a titanium alloy (Ti-6Al-4V) supplied with a width, breadth and thickness of 150 mm × 70 mm × 10 mm, respectively. The tool electrode was electrolytic copper with a square cross section of 15 mm by 15 mm and a length of 70 mm. The chemical composition and properties of the Ti-6Al-4V workpiece are shown in Tables 1 and 2 respectively, while the properties of the copper electrode are shown in Table 3. The input parameters were current (I), on-time (T_{on}), off-time (T_{off}) and voltage (V) with the range of parameter settings for machining shown in Table 4. A copper electrode was used to machine the titanium workpiece in two separate processes as depicted in the experimental set-up (Figure 1). The first was at room temperature and the second process was at a temperature of -160 ^{o}C. Cooling was done using liquid nitrogen. The EDM hole machined on the workpiece was 2 mm deep.

The subzero machining process was done using liquid nitrogen from a storage tank to maintain a temperature of -160^{o}C A polyurethylene lagged-stainless steel pipe through which the liquid nitrogen flowed into the tool electrode was used to connect the nitrogen tank to maintain a temperature of -160^{o}C.

The micro-layer defect responses investigated in this work are micro-recast layers and micro-cracks on the electrical discharged machined titanium workpiece surfaces. These were investigated using a JEOL-5600 Scanning Electron Microscope (SEM) with an EDX micro-analyzer to examine the microstructure.

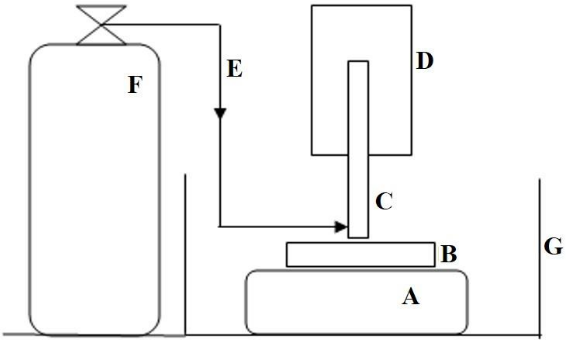

Figure 1 Schematic of the experimental set-up; A: Workpiece, B: Workpiece, C: Tool Electrode, D: Tool Holder, E: Flow line (stainless steel), F: Nitrogen Tank, G: Working Tank

Table 1 Chemical composition of the titanium alloy (Ti-6Al-4V) (wt%) used in the study

Al	C	H	Fe	N	O	V	Ti
6.0	0.08	0.015	0.25	0.05	0.2	4.0	Balance

Table 2 Properties of the titanium alloy (Ti-6Al- 4V)

Density	4.42[g/cm^3]
Hardness	326 [HBN]
Percentage elongation	10%
Percentage reduction	20%
Tensile strength	1000 [MPa]
Electrical resistivity	170[Ω cm]
Thermal conductivity	21.6[W/m K]
Melting point	1660 ^{0}C
Boiling point	3287 ^{0}C
Specific heat	0.560[J/g ^{0}C]
Mean coefficient of thermal expansion	0-100 ^{0}C/^{0}C 8.6 x 10^{-6}
Mean coefficient of thermal expansion	0-300 ^{0}C/^{0}C 9.2 x 10^{-6}

Table 3 Properties of the copper electrode used

Boiling Point	**Coefficient of thermal expansion**	**Electrical conductivity**	**Electrical resistivity**	**Melting point**	**Specific gravity**	**Specific heat**	**Thermal conductivity**
2595 [˚C]	6.6×10^{-6} [˚C^{-1}]	92% [IACS]	1. 96×10^{-6} [Ω cm]	1083 [˚C]	8.96 [g/cm^3]	0.358 [J/g ˚C]	392 [W/m K]

Table 4 Range of input parameter settings for the experiment

S/No	**Machining parameter**	**Range**	
1	Current (I) A	4.5	7.5
2	On-time (T_{on}) µs	2.0	5.0
3	Off-time (T_{off}) µs	3.0	6.0
4	Voltage (V) V	80.0	100.0

3. Results and discussion

3.1 Analysis of micro recast layers defect

The recast layer thickness on the workpiece surface as visualized using SEM is shown in Figures 2-7 and Table 5. The SEM views were obtained of the recast layers formed on the workpiece machined at room temperature and at a subzero temperature, with current of 4.5 A (Figures 2-3, Table 5A). They revealed that the layer formed on the workpiece surface machined at a subzero temperature (Figure 2, Table 5A) was thicker than that of the workpiece surface machined at room temperature (Figure 3). The three measurements of recast layer thickness formed on the workpiece surface machined at subzero temperature were 16.70 µm 10.50 µm and 15.60 µm, with average value of 14.27 µm. The workpiece surface machined at room temperature had an average thickness of 10.93 µm from three measurements, 9.09 µm, 12.40 µm, and 11.30 µm. In a similar manner, the analysis of micro-recast layers on the machined workpiece surfaces for both room and subzero temperature at a current of 5.5 A (Figures 4 and 5, Table 5B) followed a similar pattern when a current of 4.5A was used. The resulting thickenesses were 20.54 µm, 20.33 µm and 20.99 µm with an average thickness of 20.62 µm when machined at subzero temperature. Lower values were observed, 14.99 µm, 15.05 µm, and 15.10 µm, with an average of 15.05 µm for surfaces machined at room temperature.

It can be observed from Figures 6 and 7 as well as Table 5C that the thickness of the recast layer on the workpiece surface was higher when a current of 7.5A was used. This resulted in greater recast layer thickness on the workpiece surfaces machined at a subzero temperature (Figure 6) with average thickness of 24.47 µm from measurements of 30.2 µm, 20.7 µm and 22.5 µm. The average thickness of the recast layer on workpiece surfaces machined at room temperature (Figure 7, Table 5C) was 19.47 µm resulting from measurements of 19.7 µm, 20.5 µm and 18.2 µm).

According to [1, 4, 20-22], the cooling effect of liquid nitrogen improves the electrical and thermal conductivity of a copper electrode. This makes the spark stronger leading to more material melted and eroded from the workpiece surface. From the observed results, it can be concluded that recast layer thickness is also influenced by current intensity. As the current increases, the thickness of the recast layer increases as a result of more melting and more material being removed. This results in a greater proportion that is solidified as a recast layer on the machined surface. The explanation for this that the amount of molten metal which can be flushed from the spark gap by dielectric fluid is constant [1, 4, 6, 10]. Consequently, as more heat is transferred into the material when current increases, the dielectric fluid is increasingly unable to flush away the molten material, and so it builds up on the surface of the workpiece.

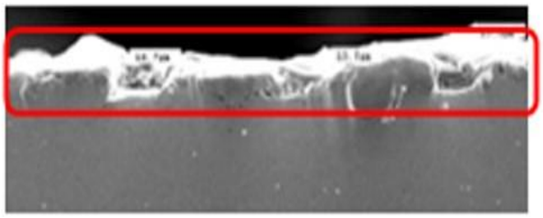

Figure 2 Recast layer thickness on a workpiece surface at a subzero temperature (I = 4.5 A) (×250)

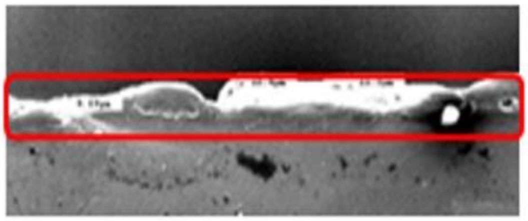

Figure 3 Recast layer thickness on a workpiece surface at room temperature (I = 4.5 A) (×250)

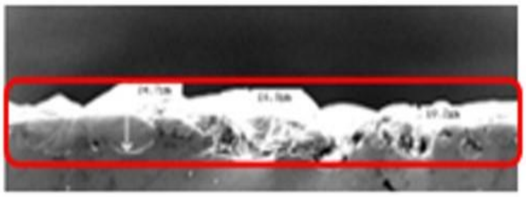

Figure 4 Recast layer thickness on a workpiece surface at a subzero temperature (I = 5.5 A) (×250)

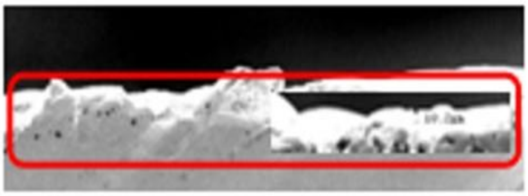

Figure 5 Recast layer thickness on a workpiece surface at room temperature (I = 5.5 A) (×250)

Table 5A Recast layer thickness on a workpiece surface at a current of 4.5 A

	Recast layer thickness on a workpiece (μm)			
	1st Reading	**2nd Reading**	**3rd Reading**	**Average**
Subzero Temperature	16.70	10.50	15.60	14.27
Room Temperature	9.09	12.40	11.30	10.93

Table 5B Recast layer thickness on a workpiece surface at a current of 5.5 A

	Recast layer thickness on a workpiece (μm)			
	1st Reading	**2nd Reading**	**3rd Reading**	**Average**
Subzero Temperature	20.54	20.33	20.99	20.62
Room Temperature	14.99	15.05	15.10	15.05

Table 5C Recast layer thickness on a workpiece surface at a current of 7.5 A

	Recast layer thickness on a workpiece (μm)			
	1st Reading	**2nd Reading**	**3rd Reading**	**Average**
Subzero Temperature	30.20	20.70	24.50	22.50
Room Temperature	19.70	20.50	18.20	19.47

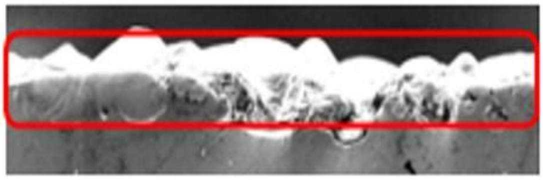

Figure 6 Recast layer thickness on a workpiece surface at a subzero temperature (*I* = 7.5 A) (×250)

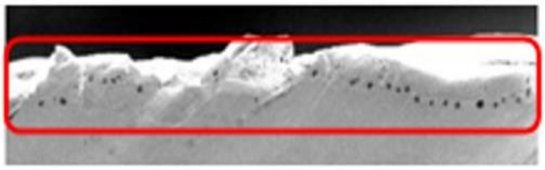

Figure 7 Recast layer thickness on a workpiece surface at room temperature (*I* = 7.5 A) (×250)

3.2 Analysis of micro-cracks defect

The analyses of the micro-cracks defect on the surfaces of the machined workpieces are shown in Figures 8 to 13. Observation of the images showing micro-crack defects on workpiece surfaces (Figures 8, 10 and 12) machined at a subzero temperature revealed more cracks than on the surfaces of workpieces (Figures 9, 11 and 13) machined at room temperature. Generally there was an increase in micro-crack defects with the use of a higher current, 7.5A, for the surfaces machined at a subzero temperature for all workpieces.

The effect of subzero temperature on the formation of micro-cracks on the machined surfaces could be due to the cooling effect on the tool electrode improving its thermal conductivity. This results in more efficient energy transfer to the machined workpiece. As the thermal conductivity of copper electrode improved during the EDM process, a constant amount of heat energy was applied for each discharge pulse. This heat energy resulted in an increased workpiece temperature and hence increased electrical resistivity [23]. The increased workpiece resistivity and its low thermal conductivity made it difficult for the workpiece to conduct the applied heat during the machining processes. With a constant amount of energy continuously applied, the result was heat accumulation in the titanium workpiece [24]. This gave rise to high residual thermal stresses coupled with rapid cooling by the dielectric fluid after each successive spark. Consequently, this led to increased crack formation while machining at a subzero temperature [4-6, 10, 12-13].

Furthermore, as current was increase from 4.5 to 7.5A, discharges struck the workpiece surface more intensely generating more heat that accumulated in the workpiece due to its higher thermal loading. This resulted in more crack on the machined surface. The effect of crack formation became more pronounced as current was increased. This finding is agreement with other studies [1, 4, 5, 12, 25].

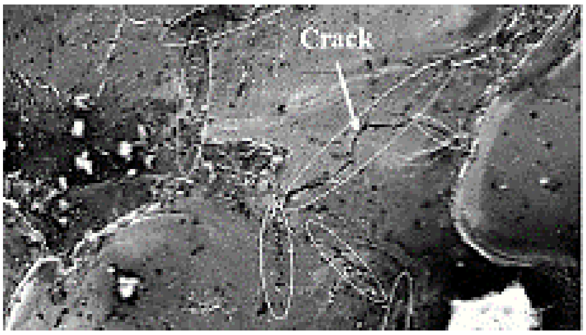

Figure 8 Micro-cracks on a workpiece surface at a subzero temperature (*I* = 4.5A) (×200)

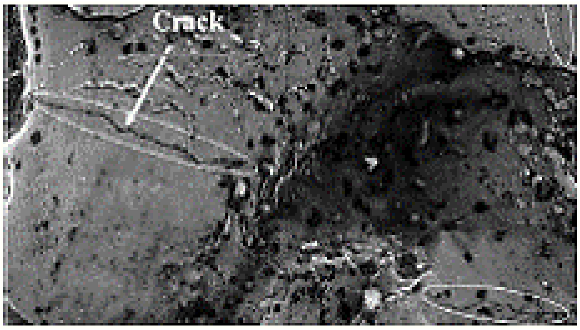

Figure 9 Micro-cracks on a workpiece surface at room temperature (*I* = 4.5A) (×200)

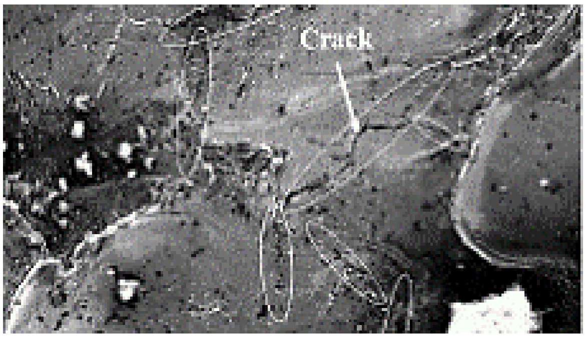

Figure 10 Micro-cracks on a workpiece surface at a subzero temperature (*I* = 5.5A) (×200)

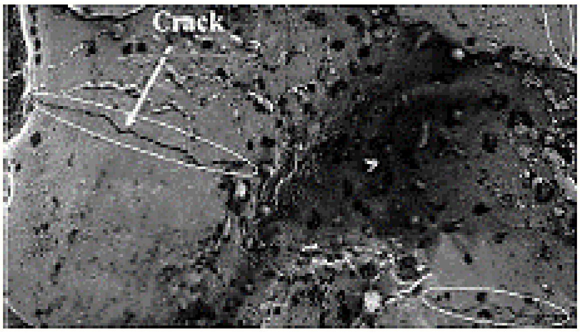

Figure 11 Micro crack on the workpiece surface at room temperature (*I* = 5.5A) (×200)

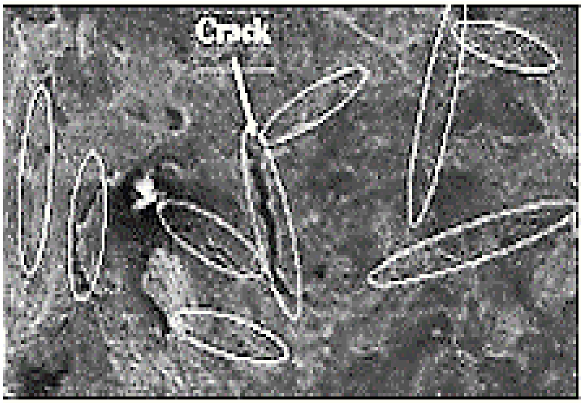

Figure 12 Micro-cracks on a workpiece surface at a subzero temperature (*I* = 7.5A) (×200)

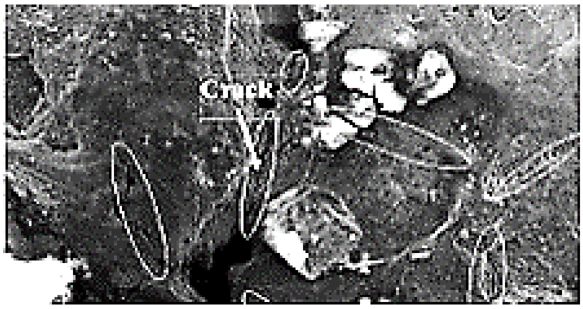

Figure 13 Micro-cracks on a workpiece surface at room temperature (*I* = 7.5A) (×200)

4. Conclusions

Analysis of microlayer defects of a functionally graded titanium alloy (Ti-6Al-4V) during EDM processing was done at subzero and room temperatures using copper as tool electrode. The micro-recast layer and micro crack-defects on the machined surface of the workpieces were examined in this study. Analysis of the results led to the following conclusions:

1. There is improvement in both the thermal and electrical conductivity of the copper tool electrode with EDM processing at a subzero temperature.
2. The improved conductivity of the tool electrode resulted in more recast layer defects on EDM machined surfaces
3. The presence of a recast layer and micro-crack defects was pronounced on the surfaces of workpiece machined at a subzero temperature.
4. Machining with low current and at room temperature caused a reduction in the thickness of the recast layer and micro-crack defects on machined surfaces.

5. Acknowledgements

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