OCCURRENCE OF GLOBULE OF DEBRIS ON SURFACES MACHINED BY WEDM

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Wire electrical discharge machining (WEDM) cuts material using the principles of electroerosion, which conclusively defines the resulting morphology of the machined surface. During the erosion process, removal of tiny particles of material (tiny globules) is achieved using a stream of dielectric. On certain surfaces, these tiny globules get stuck during the thermaltreatment and remain on the machined surface. This thesis studies these globules of debris on foursamples of two metallic materials with various heat treatment using electron microscopy.Furthermore, a part of the globule was removed using a focused iont beam, which allowed for studying its inside and analyzing the chemical composition in its individual parts.

KEYWORDS

WEDM,electrical discharge machining, titanium alloy Ti-6Al-4V, iron-rhodium alloy, globule of debris

1 INTRODUCTION

The principle behind electrothermal materialremoval is a physical occurrence known as electroerosion. Electroerosion is a physical process of material removal, which takes place on two electrodes simultaneously while immersed in a workmedium. This medium is always a dielectric, which is a liquid with high electric resistance. The discharge is created in the location of the strongest electric voltage field. This electric field sets positive and negative iont in motion, with these accelerating constantly and reaching significant speed. This occurence leads to the creation of a ionized conductive canal. At this stage, electric current starts flowing between the electrodes and an electric discharge is created, which subsequently causes a number of other particle crashes. A plasma zone is created, reaching temperatures from10 000 to 20 000 °C [McGeough 1988]. This causes melting and evaporation of material on both electrodes. At the same time, as an effect of very high temperatures, a gas bubble creates, with its pressure also reaching high values. At the moment of termination of the current, the drop in temperature causes this bubble to implode. Dielectric enters into the enclosed space, and significant dynamic forces hurl melted material from the crater. As a result of the cooling effect of the dielectric, this material subsequently solidifies and is swept away by a stream of dielectric in the form of tiny globules.The morphology of thusly created surface is composed of a large number of craters[Jameson 2001, Grote 2009].

Wire electrical discharge machining (WEDM) is a technology which allows for machining of very hard, tough, or, on the contrary, very soft materials with only one prerequisite; these materials have to be at least a bit electrically conductive. The quality parameters of the surface are influenced by an array of physical and mechanical characteristics of the machined material, and by the kind of heat treatment.It is very difficult to exploit the full potential of the final process of electrical discharge machining, for there is a large number of parameters that may change[Ho 2004, Abbas 2007, Blecha 2011a, Blecha 2011b].

2 EXPERIMENTAL SETUP AND MATERIAL

2.1 *Experimental material*

The samples for the experiment are made of a titanium alloy Ti-6Al-4V with two types of thermal treatment and of an iron-rhodium alloy.

The titanium alloy Ti-6Al-4V of chemical composition as shown in Tab. 1, was used to create 3 samples. Sample no.1- material without any additional heat treatment, samples no.2 and 3- heat treated – see Tab.3 The titanium alloy has high tensile strength of 900 MPa and excellent resistance against corrosion. It has the highest ratio of strength and weight out of all metallic materials. It is highly biocompatible and able to withstand temperatures up to 315 °C. It is used for manufacturing construction parts for weapons and airplanes, turbine blades, fasteners, medical and dental implants and sporting equipment. The initial semi-product used was a prism 18mm thick, and the machined surface of each sample was 3x18mm.

Contents	Al	Fe	O	V
Min (wt.%)	5.5			3.5
Max (wt.%)	6.75	0.25	0.2	4.5
Sample no.	**Heat treatment (HT)**			
2	Quenched and tempered 940 °C/45' / water 500 °C / two hours / air			
3	Quenched and tempered 940 °C/45' / water 570 °C / two hours / air			

Table 1. Chemical composition of titanium alloy Ti-6Al-4Vprescribed by a norm and two types of heat treatment

Sample no.4 was made of an iron-rhodium alloy (50 % Fe + 50 % Rh). Rhodium is a chemically very stable metal with melting point of 1966 °C.Having hardnessof 1246 MPa according to Vickers, it is classified as a medium hard metal and it is a relatively good conductor of heat and electricity. Most of the produced rhodium (up to 80 %) is used in automobile industry in catalysts. It is used for producing of durable chemical dishes used for burning chemical materials at high temperatures, then in an alloy with platinum (90 % Pt + 10 % Rh) to produce thermo-electrical cells, and for producing perfect mirrors for highly demanding uses. The stock used for this experiment had a diameter of 50.8 mm and thickness of 3.7 mm, and was cut in half, creating two samples 1.4 and 1.8mm thick.It has been supplied by AJA International, Inc.,and was 99.9% pure.

The hardness of sample material was measured by a hardness tester ZHR 4150AK, production series Rockwell, supplied by Zwick Roell. For titanium alloys without heat treatment was measured hardness of 35 HRC, on sample 2 was measured 46 HRC and on sample 3 was hardness of 50 HRC.The iron-rhodium alloy hardness was measured to 35 HRC.

2.2 *WEDM machine set*

The WEDM machine used in this study was high precision five axis CNC machine MAKINO EU64. To machine samples made ofthe titanium alloy, aPENTA CUT E brass wire (60% Cu and 40%

Zn)with 0.25 mm in diameter was used. For machining the iron-rhodium alloy, a copper wire was used (due to the high costs and future use of said sample, where contamination with zinc was out of the question), with the same diameter.Samples were immersed in deionized water which served as the dielectric media and also removed debris in the gap between the wire electrode and workpiece during the process. Parameters of setting machine gap voltage, pulse on time, pulse off time, wire feed and discharge current (Tab. 2) were set based on previous tests[Mouralova 2015].All samples were made using the same setting of said parameters.

Gap voltage (V)	Pulse on time (μs)	Pulse off time (μs)	Wire feed (m/min)	Discharge current (A)
40	8	88	16	22

Table 2. Machining parameters used in the experiment

3 RESULTS OF EXPERIMENT AND DISCUSSION

The machined surfaces were cleaned off in an ultra-sound cleaner and studied using electron microscope (SEM) LYRA3 supplied by Tescan. This device is equipped with energy-dispersion detector of X-rays (EDX), which allowed for studying changes in chemical composition of the machined material caused by WEDM. Another device, with which is the LYRA3 microscope equipped, is the focused iont beam (FIB). It was used for the removal of one half of the globule using targeted ionic spattering.

3.1 *Morphology of sample 1 - Ti-6Al-4V without heat treatment*

The surface of the titanium alloy without heat treatment is covered with a number of craters (see Fig. 1), and with completely melted and then cooled material mixed from the wire electrode and the workpiece, which is observable from the EDX local analysis shown in Fig. 2 and in Tab. 3. Intensive difusion actions between the wire and the workpiece have been studied in many other construction materials[Mouralova 2016, Kumar 2013a].However, no globule of debris can be found on the entire surface of the sample.

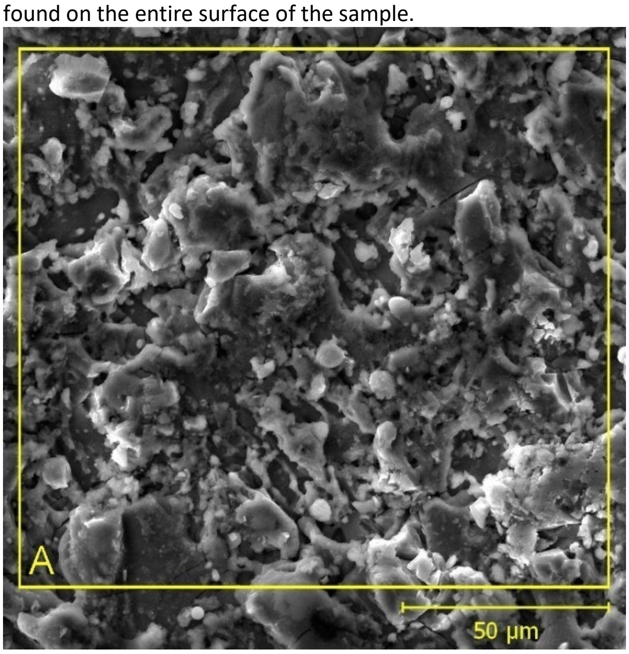

Figure 1. Morphology of surface of sample no. 1 (SEM), 1 400x magnification

Al	Ti	O	V	Fe	Zn	Cu
2.8	64.7	20.7	0.4	2	1.2	8.2

Table 3. Analysis of chemical composition EDX (wt. %) of titanium alloy without heat treatment

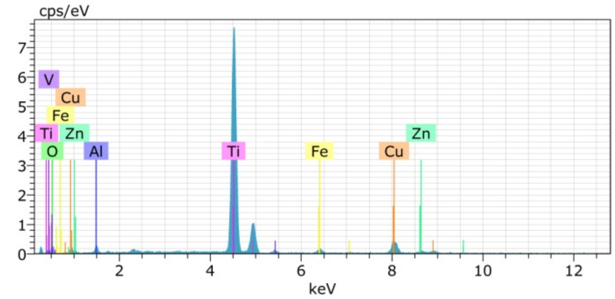

Figure 2. Analysis of chemical composition in placeAaccording to Fig. 1

3.2 *Surface morphology of sample no.2 - Ti-6Al-4V with heat treatment (tempered at 500 °C)*

The surface morphology of this sample is created by craters too, but large number of globule of debris with diameter from 1μm to 10 μm are present as well (Fig. 3 (c)). These globules are evenly distributed on the whole surface. Using FIB, half a globule was sputtered, which allowed for studying its inner space and revealed if it is hollow or not. 5 globules of various diameters were sputteredin this manner, none of which were hollow.One such partially sputteredglobule is shown in Fig. 3 (b).Occurrence of similar globules was studied in materials Inconel 706 [Sharma 2015], $Ti_{50}Ni_{50-x}Cu_x$ [Manjaiah 2015], steel HSLA [Azam 2016] and pure titanium [Kumar 2013b] as well.None of these studies, however, performed sputtering of the globules and chemically analyzed its insides.

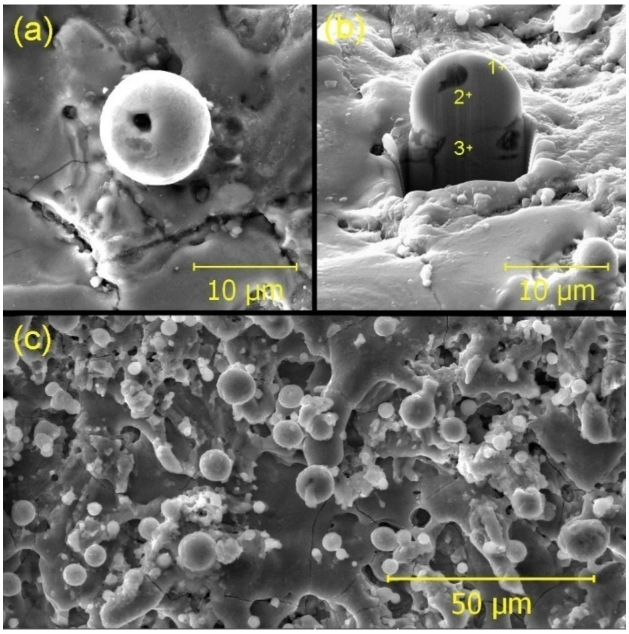

Figure 3. Morphology of surface of sample no. 2 (SEM) (a) globule of debris 4 000x magnification, (b) globule of debris after FIB 4 000x magnification, (c) globule of debris on surface1 4000x magnification

Using FIB technology, it was possible to study the inner surface of individual globules and perform an EDX analysis of chemical composition. Places of detection were chosen subsequently; close to the surface of the globule, in its core and in the contact area with the machined material (Fig. 3 (b)). The values measured with this analysis were put into Tab. 4. Most oxygen (O) was contained in the surface layer of the globule (measure place no.1), most copper (Cu) wasin the contact area with the base material. The core is made mostly of titanium (Ti), as it is the base element of the machined material.

Place of measurement	Al	Ti	O	V	Zn	Cu
1	2.6	65.8	26.8		0.3	4.5
2	2.8	81.3	9.3		0.3	6.3
3	3.5	78.4	2.8	1.5	1.2	12.6

Table 4. Chemical composition analysis EDX (wt. %) of globule of debris in sample no. 2, in places of measurement according to Fig. 3 (b)

3.3 Surface morphology of sample no.3 – Ti-6Al-4V with heat treatment (tempered at 570 °C)

A large number of tiny globules of diameters from 1 µm to 10 µm can be found on the whole surface of sample no.3. They are equally distributed on the whole studied surface of the sample (Fig. 4 (c)). After sputtering half of the globule, its chemical composition was studied in individual places according to Fig. 4(b), results of which were put into Tab. 5. All three places shown contents of copper from the electrode in amounts from 8.9 to 16.3 wt.%. The surface in measurement placeno.1 again shows a higher oxygen content, 25.6 wt.%.

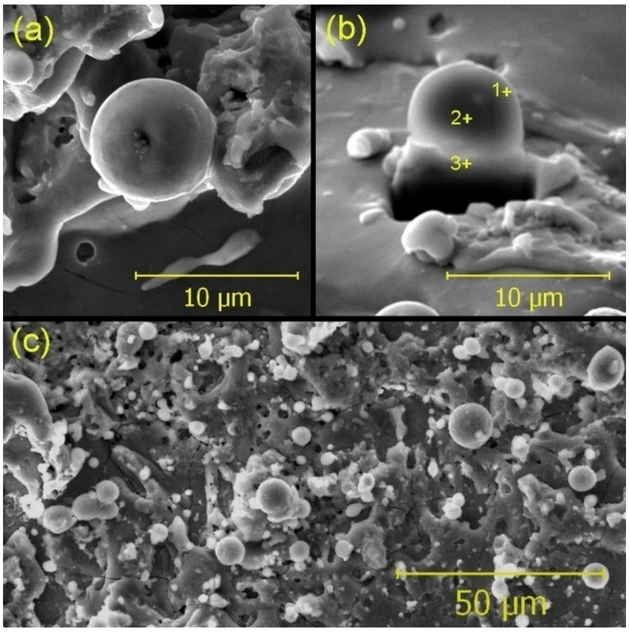

Figure 4. Morphology of surface of sample no.3 (SEM) (a) globule of debris 6 000x magnification, (b) globule of debris after FIB 6 000x magnification, (c) globule of debris on sample surface 1 400x magnification

Place of measurement	Al	Ti	O	Zn	Cu
1	2.8	62.3	25.6	0.4	8.9
2	2.3	76.1	6.7		14.9
3	3.1	73.7	6.9		16.3

Table 5. Chemical composition analysis (EDX) (wt. %) in globule of debris on sample no. 3, in places of measurement according to Fig. 4 (b)

3.4 Surface morphology of sample no.4- iron-rhodiumalloy

The surface of the sample madeof the iron-rhodium alloy is covered with tiny globules with diameters from 1 to 20 µm on its entire surface. These globules of debris are mainly present in deep craters, which they fill up almost entirely, as seen in Fig. 5(c). Using FIB, halves of 5 different globules of various diameters were sputtered off, and none turned out to be hollow.This halving then allowed for chemical composition analysis in places as in Fig. 5 (b). The detected values of individual elements were put into Tab. 4.

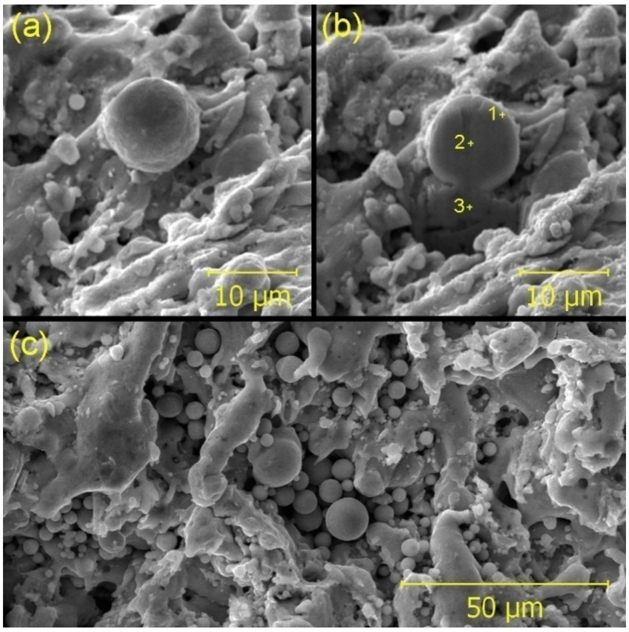

Figure 5. Morphology of surface of sample no.4 (SEM) (a) globule of debris 4 000x magnification, (b) globule of debris after FIB 4 000x magnification, (c) globule of debris on sample surface 1 400x magnification

According to EDX, the core of the globule is in 95.5 wt.% made of copper, which is the wire electrode material. Slight oxidation took place on the surface of the globule, leading to a 3.3 wt. % content of oxygen. The machined material elements iron (Fe) and rhodium (Rh) are mostly contained near the surface of the globule and its contact area with the machined material. Both these elements show only 4.2 wt.% content in the core of the globule.

Place of measurement	O	Rh	Fe	Cu
1	3.3	17.5	5.6	73.6
2	0.3	2.5	1.7	95.5
3	0.8	10.6	3.7	84.9

Table 6. Chemical composition analysis EDX (wt. %) of globule of debris on sample no.4, in places of measurement according to Fig. 5 (b)

4 CONCLUSIONS

As a result of temperatures from 10 000 to 20 000 °C, evaporation of the workpiece, electrode and the used dielectric material takes place during the erosion process, along with formation of gas bubbles. At the moment of termination of the current between the workpiece and wire, a temperature drop takes place and significant dynamic forces hurl molten material from the crater. The removed material is swept away from the location of the cut by a stream of dielectric fluid.

Those tiny globules of debris, however, remain on the machined surface with certain materials and with their various heat treatment. Subject of this experiment were two metallic materials, a titanium alloy Ti-6Al-4V with and withoutheat treatment and an iron-rhodium alloy. Only one of these 4 samples shown no sign of these globules, and that was thermally untreated titanium alloy. This sample, however, shown the same hardness of 35 HRC as the sample made of the iron-rhodium alloy, where these globules were detected. It can therefore be assumed that the presence of these globules is not dependent solely on the hardness of the machined material.

Using FIB, it was possible to study the inside of these globules, with 5 globules being studied on each sample. Based on this study, it is safe to say all of the studied globules were not hollow. It also can be said, based on the chemical composition analysis of these globules, that oxidation takes place on their surface.The globules studied on the titanium alloy are mainly composed of the workpiece material, with content of copper below 16.3 wt.%. In contrast, the globules on the iron-rhodium alloy were made mainly of copper, and the workpiece material content was detected to be only up to 23.1 wt.%.The detected difference in concentration is caused by lower solubility of copper in the titanium alloy than in the iron-rhodium alloy. This difference occurs after both the workpiece and electrode material melts and cools on the studied surface after the WEDM. This can be observed from the phase diagrams of individual alloys of the studied workpiece metal and the electrode metal. [Wriedt 1990].

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REFERENCES

[Abbas 2007] Abbas, N. M., Solomon, D. G., & Bahari, M. F. (2007). A review on current research trends in electrical discharge machining (EDM). International Journal of machine tools and Manufacture, 47(7), pp. 1214-1228.

[Azam 2016] Azam, M., Jahanzaib, M., Abbasi, J. A., Abbas, M., Wasim, A., & Hussain, S. (2016). Parametric analysis of recast layer formation in wire-cut EDM of HSLA steel. The International Journal of Advanced Manufacturing Technology, pp. 1-10.

[Blecha 2011a] Blecha, P., Blecha, R., Bradac, F. (2011). Integration of Risk Management into the Machinery Design Process. In Mechatronics Springer Berlin Heidelberg, pp. 473-482.

[Blecha 2011b] Blecha, P., & Prostrednik, D. (2011). Influence on the failure probability. Annals of DAAAM & Proceedings, pp. 11-13.

[Grote 2009] Grote, K. H., Antonsson, E. K. (2009).Springer handbook of mechanical engineering (Vol. 10). Springer Science & Business Media, ISBN 9783540491316.

[Ho 2004] Ho, K. H., Newman, S. T., Rahimifard, S., & Allen, R. D. (2004). State of the art in wire electrical discharge machining (WEDM). International Journal of Machine Tools and Manufacture, 44(12), pp. 1247-1259.

[Jameson 2001] Jameson, E. C. (2001). Electrical discharge machining. Society of Manufacturing Engineers. ISBN 0-87263-521-X.

[Kumar 2013a] Kumar, A., Kumar, V., & Kumar, J. (2013). Multi-response optimization of process parameters based on response surface methodology for pure titanium using WEDM process. The International Journal of Advanced Manufacturing Technology, 68(9-12), pp. 2645-2668.

[Kumar 2013b] Kumar, A., Kumar, V., & Kumar, J. (2013). Experimental Investigation on material transfer mechanism in WEDM of pure titanium (Grade-2). Advances in Materials Science and Engineering.

[Manjaiah 2015] Manjaiah, M., Narendranath, S., Basavarajappa, S., & Gaitonde, V. N. (2015). Investigation on material removal rate, surface and subsurface characteristics in wire electro discharge machining of Ti50Ni50-xCux shape memory alloy. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications.

[McGeough 1988] McGeough, J. A. (1988). Advanced methods of machining. Springer Science & Business Media, ISBN 9780412319709.

[Mouralova 2016] Mouralova, K., Bednar, J., Kovar, J., Mach, J., (2016) Evaluation of MRR after WEDM depending on the resulting surface. Manufacturing TECHNOLOGY, pp. 396-401. ISSN: 1213-2489.

[Sharma 2015] Sharma, P., Chakradhar, D., & Narendranath, S. (2015). Evaluation of WEDM performance characteristics of Inconel 706 for turbine disk application. Materials & Design, pp. 558-566.

[Wriedt 1990] Wriedt, H. A., & Murray, J. L. (1990). Binary alloy phase diagrams. ASM handbooks online.

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