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*aluminium composites,*
*reinforcing phase,*
*electro-discharge machining*

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# EFFECT OF GRANULARITY OF REINFORCING PARTICLES $Al_2O_3$ ON EDM PROCESS OF ALUMINIUM MATRIX COMPOSITES

The study discusses issues related to the process of electro-discharge machining (EDM) composites based on Al + 20% Si + 5% Fe + 3% Cu + 1% Mg matrix manufactured using a powder metallurgy method. Ten percent by volume of $Al_2O_3$ grains of 3, 9, 23 and 53µm sizes with irregular sharp edges represented the reinforcing phase. EDM was performed with a machine equipped with a RLC generator using different (computational) discharge energies varied in steps within the 0.044 - 2.268mJ range. The tests measured volumetric productivity of EDM (Vw) and roughness (Ra) of the machined surface. In addition, the researchers provided selected SEM images of ED-machined surfaces with some results of X-ray microanalyses of chemical composition performed in cavities and on the surfaces of irregularities. They also provided SEM images of $Al_2O_3$ grains adhering to the machined surface of the composite, showing the mechanism of erosion of dielectric particles in EDM conditions. They demonstrated that the energy of single discharges (Ei) was the main parameter effecting the process and results of EDM. The volumetric productivity of the process (Vw) and roughness of the machined surface (Ra) increase with growth of energy ($E_i$) and, at the same time, surface integrity (SI) changes.

## 1. INTRODUCTION

The electro-discharge machining (EDM) process is commonly used in industrial applications to shape components made from hard materials (such as quenched steels, sintered carbides or PCD) and materials difficult or impossible to machine using conventional methods (heat-resistant or high temperature creep-resistant steels and alloys, tungsten alloys, etc.). As the number of applications of metallic composites reinforced with various ceramic particles (some containing large volumes of such material) continues to increase, EDM provides an efficient answer to problems related to the manufacture of parts from such materials. For instance, EDM can successfully replace grinding as a method of final shaping and sizing complex items. The process is particularly useful for making small holes (< 1mm) reliefs, seats and similar recesses in composite materials. It is known [1-3] that the reinforcing phase of composites is very hard to machine using conventional methods, even with state-of-the-art tools. Thus, EMD provides a method of working

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metallic composites alternative to machining. EDM removes materials by generating electric discharges in the working gap (between the electrode/tool and the worked item) filled with liquid non-conductor. Discharges produce high local temperatures estimated at from a few up to a dozen or so thousands of degrees Kelvin [4] At these points the material rapidly melts, evaporates and even sublimates. As a result of the implosion effect (occurring after the bursting of the gas bubble), particles of molten material (and occasional mechanically separated particles) are ejected to the surrounding dielectric where they solidify, forming “erosion products”. Ceramic particles (typically non-conducting), such as $Al_2O_3$ or $Si_3N_4$, featuring also high thermal resistance, add significant difficulty to the working of metallic matrix composites. As demonstrated by former research [2],[3],[5] comparing the processes and results of ED-machining composites and matrices free from reinforcing particles, machining performances for composites were always worse than for matrices. Also the volumetric share of the reinforcing phase in a composite has a very important effect on the performance of EDM; for instance, increasing the content of the reinforcing phase ($Al_2O_3$) from 2.5% to 20% resulted in a 4-fold drop in processing efficiency (Vw) [5],[6],[7].

## 2. RESEARCH

Studies tested composites with Al20Si5Fe3CuMg matrix, manufactured from powder by Showa Denko, Japan. The composites had a fixed, 10%, volumetric share of the reinforcing phase $Al_2O_3$. See Table 1 for designations, compositions and properties of the tested composites.

Table 1. Designations, contents and properties of composites

| **Material designation** | **Matrix** | **Reinforcing phase ($Al_2O_3$)** | | **Properties** | | |
|---|---|---|---|---|---|---|
| | | **% vol.** | **Granularity µm** | **Hardness HRB** | **Rm MPa** | **α 10-6 ·K-1** |
| K0 | Al. + 20% Si + 5% Fe + 3% Cu + 1% Mg | - | - | | 500 | |
| K3 | | 10 % | 3 | 98 | 357 | 17.4 |
| K9 | | | 9 | 103 | 453 | 15.7 |
| K23 | | | 23 | 101 | 466 | 15.4 |
| K53 | | | 53 | 102 | 396 | 15.1 |

Samples for testing were manufactured using powder metallurgy (PM) methods. A process of hot extrusion at 420°C with 20:1 cross-section reduction produced microstructure illustrated in Fig. 1 (9µm granularity).

The samples were machined using a spark erosion machine, model EDEA-25, with a RLC generator and 10mm diameter M1E electrodes with central 1.5mm channel for feeding dielectric (cosmetic kerosene). A free machining technique was used (Fig. 2). Each worked sample had 8mm in diameter.

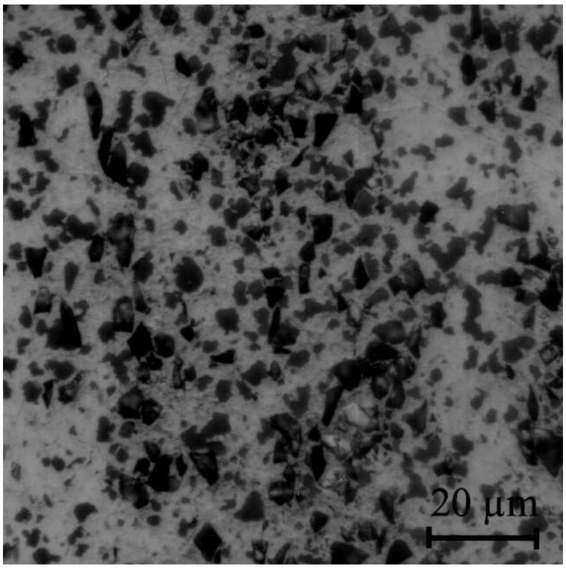



Fig. 1. Microstructure of composite K9

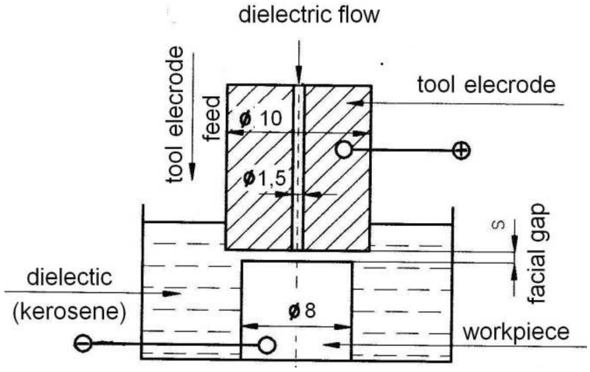



Fig. 2. Free EDM process diagram

The RLC generator (6 presets) enabled the generation of variable computational energies for a single impulse (Ei; see Table 2) at the working voltage (Ur) of 180V.

Table 2. Energies of single EDM impulses for composites

| Designation | Ei 1 | Ei 2 | Ei 3 | Ei 4 | Ei 5 | Ei 6 |
|---|---|---|---|---|---|---|
| Value [mJ] | 2.268 | 1.555 | 0.356 | 0.209 | 0.165 | 0.044 |

The tests measured volumetric productivity of EDM (Vw) and roughness (Ra) as a function of energy (Ei) and granularity of the reinforcing phase. Roughness was measured using a scanning profile measurement gauge, model FORM TALYSURF 2.

## 3. TEST RESULTS AND ANALYSIS

See Figs. 3 and 4 for the effect of Ei on Vw for different granularities of $Al_2O_3$ and the effect of granularity on Vw for given Ei, respectively.

The diagrams show that Ei has the largest effect on Vw (Fig. 3) and, as expected, Vw increases with growth of Ei.

The EDM process performs best for the matrix. The presence of ceramic (dielectric) particles in the composite always reduces the performance of EDM. Also the size of the reinforcing particles affects the performance: the growth from 3 to 53µm in the tests produced efficiency reduction ranging from 14% to 18% (Fig. 4). Ceramic particles, partially molten and separated from the matrix base or cracked, are being pulled out from the worked material surface during electro-discharge machining, among others as a result of the implosion effect, and migrate to the inter-electrode space.

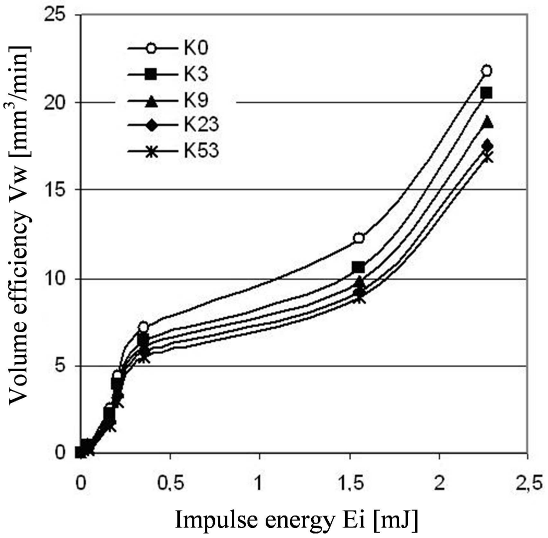



Fig. 3. Volume efficiency Vw vs. Ei

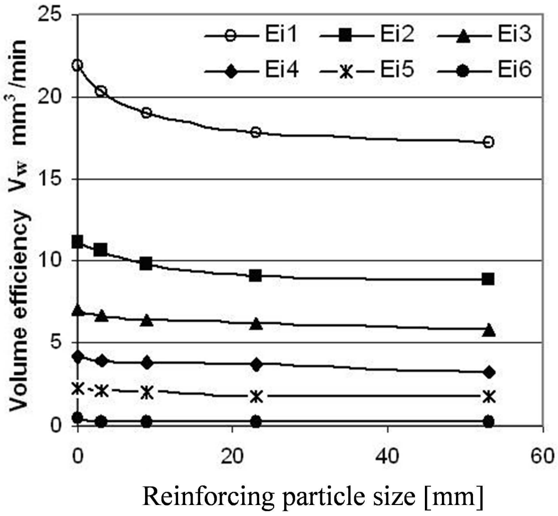



Fig. 4. Volume efficiency Vw vs. reinforcing particle size at different Ei

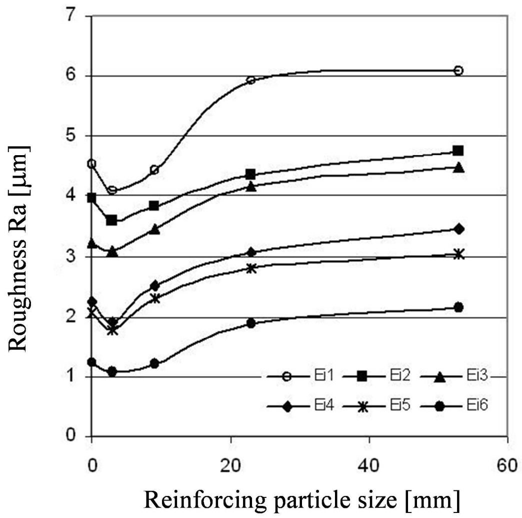



Fig. 5. Roughness Ra vs. reinforcing particle size at different Ei

The larger particle sizes the harder the process, which explains the loss of EDM performance. Fig. 5 shows the effect of granularity of the reinforcing phase on Ra of the machined surface for various Ei, larger Ei means higher Ra. As it can be seen from the curves, the effect of granularity of the reinforcing phase on roughness is complex. For particle sizes of approx. 3µm the characteristic minimum $R_a$ was noted for all Ei. Ra for K3 was smaller than for the matrix of K0. To explain this, it would be helpful to perform further detailed tests using composites reinforced with sub-micron- (< 1μm) or nanometer-sized grains. It is likely, that the process of electro-erosion of such composites will be different than that described in the literature [8],[9] et al]. Fig. 6 shows a sample surface profilogram for composite K9.

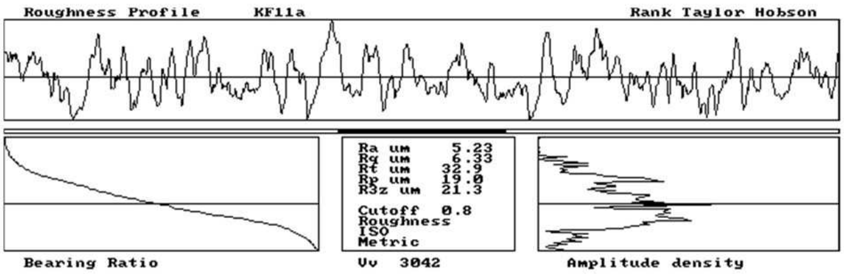



Fig. 6. Surface profilogram for K9

Fig. 7 shows some SEM images of ED-machined surfaces and X-ray micro-diffraction patterns for chemical composition determinations made for cavities and surfaces of irregularities of the machined surfaces.

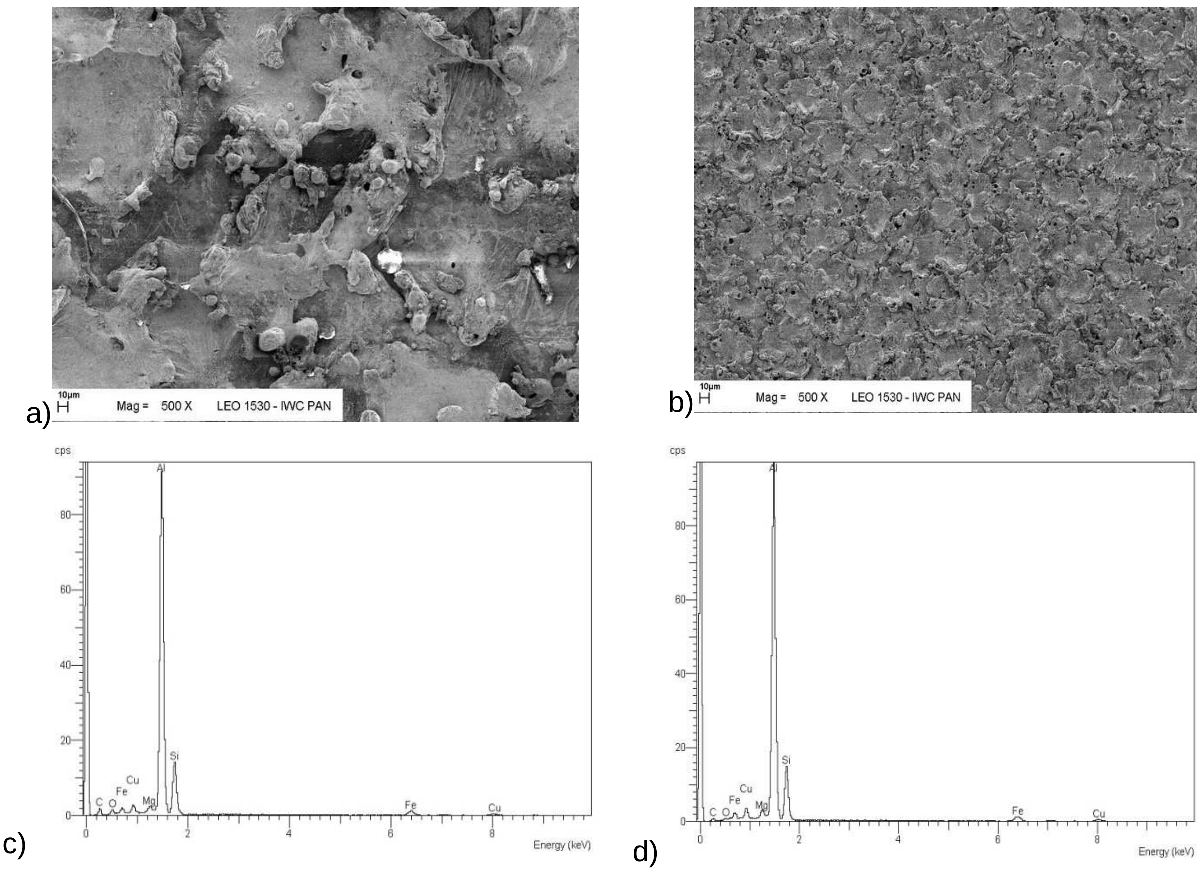
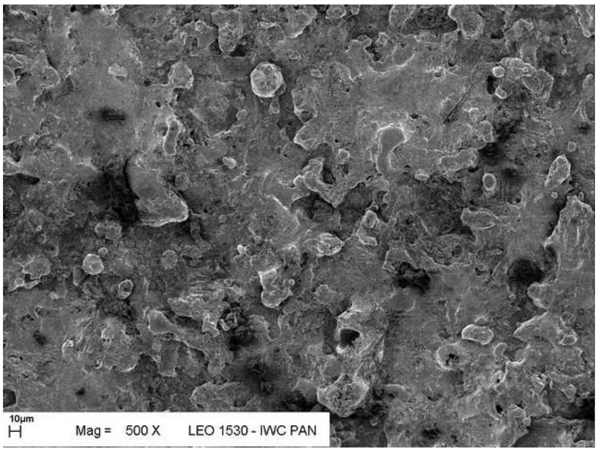
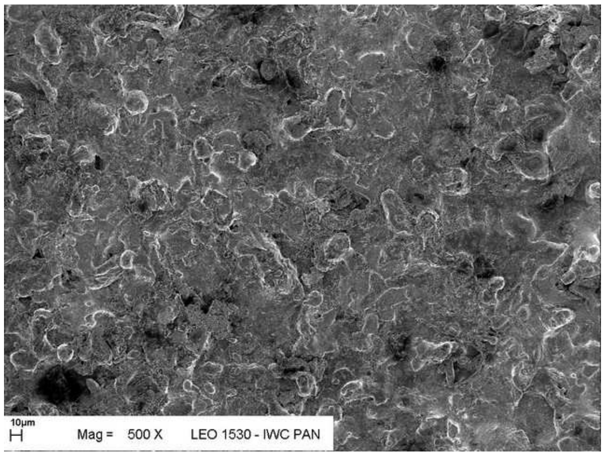


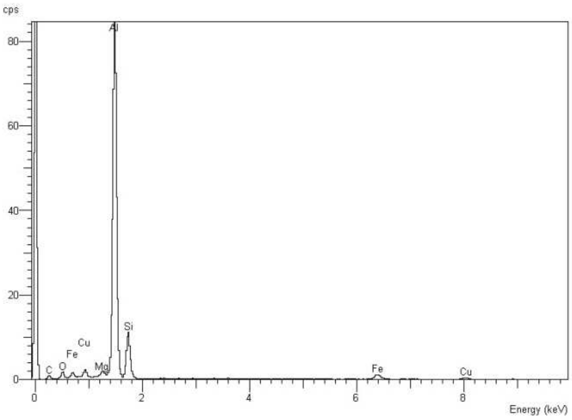

Fig. 7. SEM image of ED-machined surface for matrix: a) Ei 1; b) Ei 6; c) micro-diffraction pattern for surface ”a” -- bulge and d) cavity



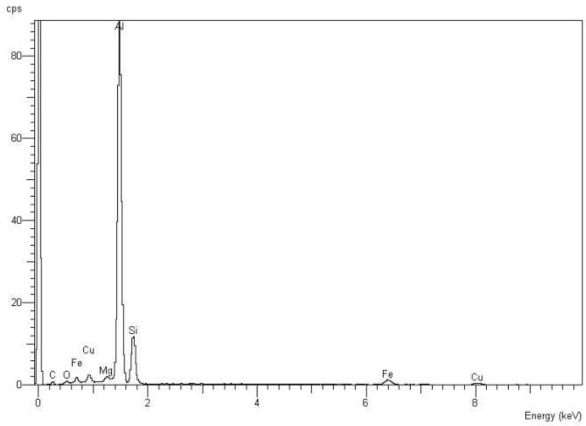

a)




b)

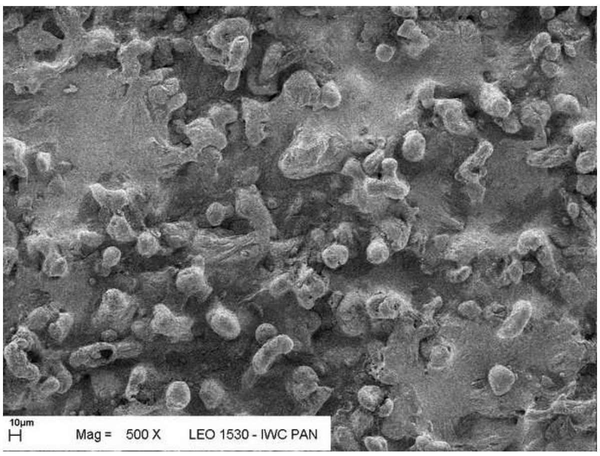



c)

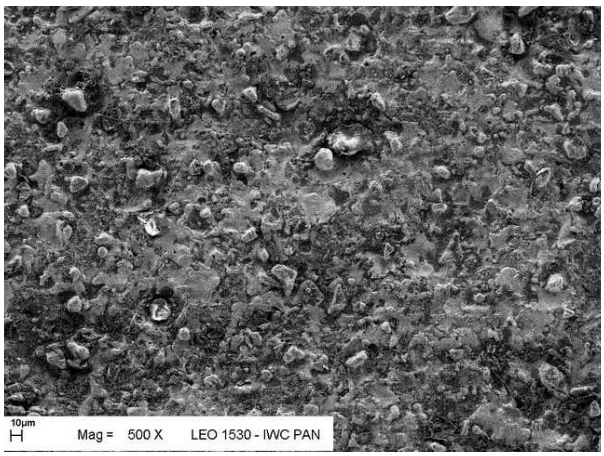



d)

Fig. 8. SEM image of ED-machined surface for composites worked with energy Ei6: a) composite K3; b) composite K9; c) micro-diffraction pattern for surface " a" - bulge and d) cavity

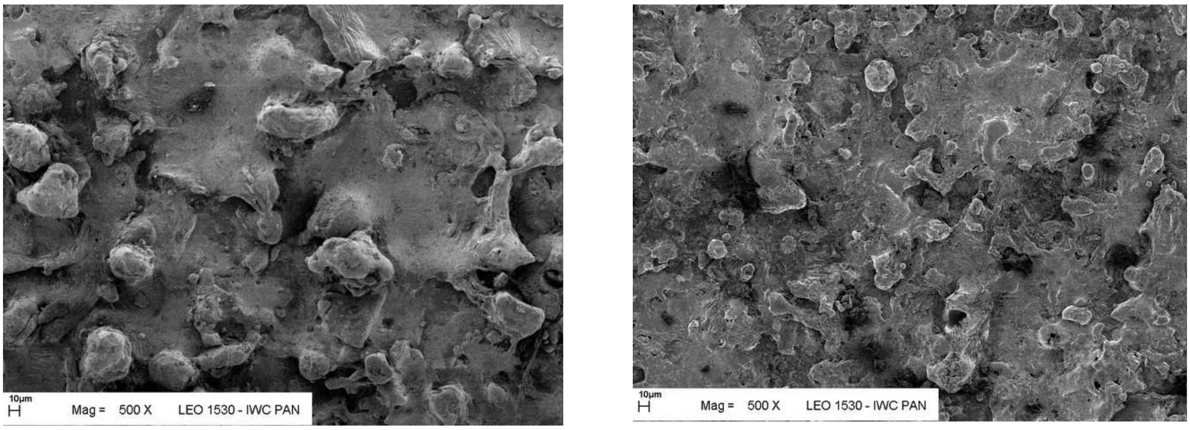



a)



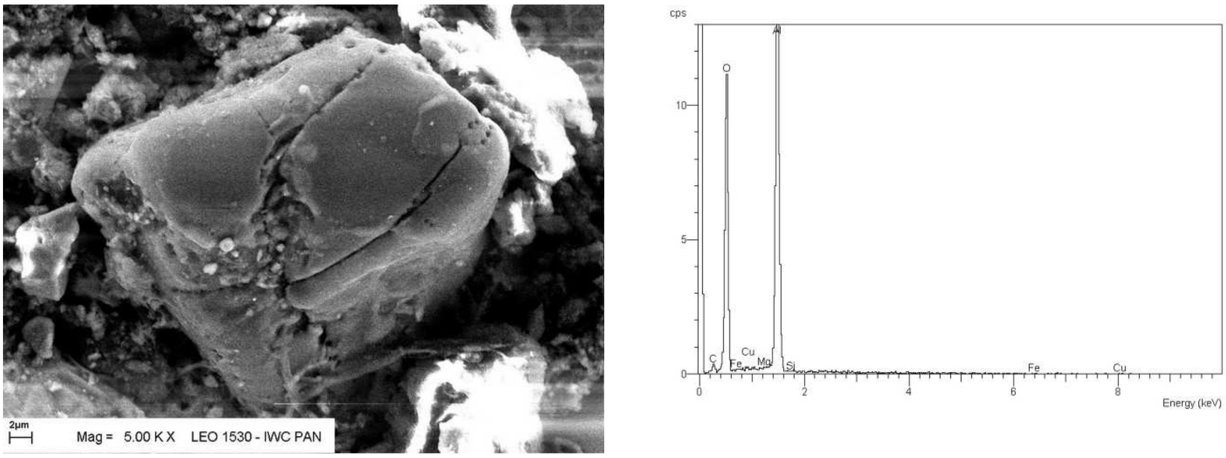

b)

Fig. 9. SEM image of ED-machined surface for composite K23: a) Ei 1, b) Ei 6




a) b)

Fig. 10. SEM image of ED-machined surface for composite K53: a) Ei 1; b) Ei 6




a) b)

Fig. 11. SEM image of grains from the surface of composite K53 after EDM with energy Ei 6 a) micro-diffraction b) pattern for grain

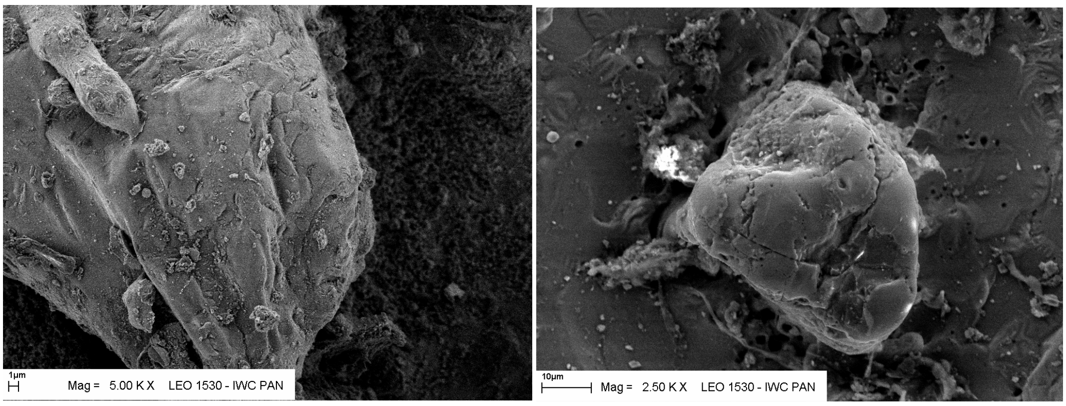



Fig. 12. SEM image of grains (as in Fig. 11) at different surface points

The figures enable tracking the effect of reinforcing particle granularity on the process and performance of electro-erosion of composites. The surface texture of ED-machined matrix (Fig. 7) is typical, similar to that observed for ED-machined surfaces of homogeneous metals: cavities (craters) from electric discharges, omnidirectional structure resembling point pattern, clear crater edges from melting and rapid solidification, surface with small spherical beads adhering to the base. X-ray microanalysis of cavities and bulges shows no significant differences between the chemical compositions of the tested layers. Note the insertion of carbon: more on the bulges and less in the cavities. Carbon diffused to superficial layer (SL) as a result of pyrolysis of the dielectric (kerosene). Also, studies [2],[9],[10] demonstrated that unevenness of carbon distribution is larger on bulges than in cavities.

As the size of the reinforcing particle increases, texture of the machined surface evolves (Figs. 8-10). The surface contains more and more adherent particles with sizes similar to those of the reinforcing particles. The surface texture is becoming increasingly island – type and not so much point - type (Fig. 10a).

The result of X-ray microanalysis for composite K3 is not much different from that for the matrix (Figs. 7c and 7d). Also, bulges carry more carbon than cavities.

Figures 11 and 12 show large magnifications of grains adhering to the machined surface of composite K53 (53μm grain size). We can see the grains are cracked (most likely as a result of thermal stress) and their corners are clearly rounded. $Al_2O_3$ grains used to reinforce this composite used to have sharp edges, which can be seen in the picture of their microstructure (Fig. 1). X-ray microanalysis (Fig. 11b) makes it clear that these are $Al_2O_3$ grains that were partially melted on the edges by electric discharges in the inter-electrode gap and cracked on their surfaces on re-solidification as a result of highly uneven distribution of temperature. These grains were removed from the worked layer but did not leave the machined space and fused with the base as a result of rapid cooling of molten products in the plasma channel. The looks and X-ray patterns of similar particles set on machined surfaces are very much similar to one another.

The foregoing results confirm earlier conclusions [9] on the process of erosion of composites reinforced with ceramic particles as well as important effect of such particles, single discharge energy and duration on the erosion process. Physical and mechanical properties of grains, including specifically thermal properties (such as melting, evaporation and sublimation temperatures; heat conductivity and capacity; heat conductance factor; expansion; thermal diffusivity; etc.), have an important effect on the process. Similar observations are contained in studies [11],[12], et al and other works.

## 4. CONCLUSIONS AND NOTES

Conclusions from reviewing the results of ED-machining of metallic composites with aluminium matrix, reinforced with ceramic particles are as follows:

– Volumetric productivity of EDM (Vw) depends to much extent from the energy of the single discharge (Ei) and other electric impulse conduction features (depending on generator type).

- Vw decreases significantly with growth of composite reinforcing particles grain size: by 14 to 18 percent for the tested $Al_2O_3$ grains. Similar drop can be expected in presence of $Si_3N_4$ grains.
- Roughness of the machined surface (Ra, Rz) depends on Ei and features of individual impulses as well as on composite reinforcing grain size. The larger particles the higher Ra after EDM.
- Geometric textures of ED-machined surfaces (SI) are slightly different. According to [9 et al] SI of a composite containing SiC particles resembles SI of the matrix while SI of composites containing $Al_2O_3$ or $Si_3N_4$ particles are similar to each other and clearly different from SI of the matrix.
- For larger Ei and longer impulses, IS of $Al_2O_3$ and $Si_3N_4$ composites deviates from omnidirectional point scatter pattern and resembles islet pattern. Superficial Layer (SL) of composites containing $Al_2O_3$ and $Si_3N_4$ particles contain more micro-cracks [9].
- SL with modified metallographic and phase structures with uneven layer thickness, resulting from random nature of events taking place during electrical discharge, are observed. The thickness and chemical and phase compositions of the layer and the distribution of erosion traces on the surface depend mainly on the process specifications and reinforcing particles type [9].
- Granularity, chemical composition and appearance similar to those of the reinforcing particles, either protruding or fused with the base, are frequently found on (W)ED-machined surfaces of composites strengthened with dielectric ceramic particles ($Al_2O_3$, $Si_3N_4$) [9].
- Increased content of carbon originating from pyrolysis of the dielectric (hydrocarbon), inserted by way of diffusion during discharge, is found in SL of ED-machined surfaces, specifically on the tops of surface irregularities.

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