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## Selected Aspects of Electrodischarge Milling of Aluminum Alloy-Based Metal Matrix Composite with SiC Reinforcement

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### Abstract

In the paper an experimental investigation of the electrodischarge machining of Al-SiC composite material was presented. This material belongs to a group of metal matrix composites (MMCs). Due to enhanced mechanical properties and relative lightweight MMCs are currently implemented in advanced branches of industry such as aerospace, nuclear and automotive and its area of application will significantly increase in the nearest future. However, machining of MMCs remains a challenging task. Because of structural heterogeneity they are difficult-to-machine. It's machining by conventional and also by non-conventional way is not effective. The paper reports an experimental investigation on electrodischarge milling (3D-EDM) of Al-SiC composite. During the research, the following three input factors were taken into account: working voltage, current amplitude and pulse duration. The experimental part consists of fifteen tests carried out according to the three-level experimental plan. As output factors machining speed and accuracy, tool wear and surface roughness were selected. Also, based on SEM photographs, a qualitative discussion on machined surface integrity was presented. The obtained results prove, that EDM can be effectively applied to machine aluminium alloy-based metal matrix composites with SiC reinforcement.

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*Keywords:* electrodischarge machining; EDM; milling, MMC; aluminium alloy; SiC reinforcement.

### 1. Introduction

Nowadays the industry is focused on the production of smaller and more precise products with much better properties and made of new materials such as advanced ceramic or composite materials. Metal Matrix Composites (MMCs) are composite materials with metallic matrix (usually light metal- or alloy-based on aluminium, magnesium or titanium) and reinforcement (Al<sub>2</sub>O<sub>3</sub>, SiC, TiB<sub>2</sub>, TiC particles or continuous carbon/silicon carbide fiber) [1, 2]. The metal matrix distributes the loading and provides support for the structure while the particles or fibers reinforcement provide advantageous physical, mechanical or thermal performance. Therefore MMCs are lightweight and have high specific properties (e.g. strength, stiffness and wear resistance), becoming attractive alternative in demanding industrial

applications. This pulls the out dynamic development of MMCs for their use in automotive, aerospace and nuclear industry as a replacement for traditional materials.

MMCs are produced by several fabrication methods (i.e. metal injection molding, friction stir process, mechanical alloying, squeeze casting technology, continuous binder-powder coating etc.) [2]. However to prepare final shape of part, a secondary process is usually required. Structural heterogeneity and high specific properties of MMCs pose many challenges to the machining process, which in many cases leads to poor surface quality, residual stress and rapid tool wear. Conventional machining (cutting) of MMCs are connected with relatively high geometrical accuracy, however, due to mechanical nature of the process, it introduces plastic deformation and excessive heat generation what decreases workpiece surface layer quality. Unconventional machining

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methods allows to removing material with almost no tool wear and lower cost in comparison to cutting. However, it is worth to underline, that advantage of unconventional methods over cutting is noticeable only during machining difficult to cut materials and complicated shapes. In other cases, due to high energy consumption, application of such methods is not competitive.

The research in area of unconventional machining of MMCs focuses mainly on laser (assisted) machining, abrasive water jet machining and electrical-discharge machining [1]. However, most of the unconventional machining processes lead to machining defects, therefore further investigations are necessary in order to understand in details material removal and surface damage mechanism.

In the paper electrodischarge machinability of aluminium alloy-based metal matrix composite with SiC reinforcement was investigated. Electrodischarge machining (EDM) allows to machine conductive materials irrespective of their chemical composition and mechanical properties (such as hardness). During EDM the electrical energy is changed into thermal energy during a series of discrete electric discharges which occur between two electrodes (workpiece and tool) immersed in a dielectric medium. The material is removed by melting and evaporation due to the thermal energy from a series of electric discharges generated between these electrodes. The dielectric medium between the tool and the workpiece provides the optimal conditions for spark generation, regulate thermal conditions and flushes the debris formed in the gap. The tool and the workpiece are connected to the pulse generator of the discharge voltage from up to a few hundred volts and current ranges up to tens of amperes [3, 4, 5]. EDM is a non-contact process and machining forces are negligible, therefore it can be used to machine thin, fragile and high-aspect ratio shapes.

The efficiency of EDM process is connected with optimal selection of process parameters (voltage and current signal), however in comparison to machining of traditional (metals or alloys) materials during machining of MMCs following issues should be taken into account [1]: (i) the difference of material removal mechanism of metal matrix and particle reinforcement, (ii) the material of reinforcement (especially its electrical properties are important), (iii) proportion or volume ratio of reinforcement to the matrix material.

EDM can be carried out in different kinematic variants, however, in application to MMCs the most exploited is wire EDM (almost 60 research papers published since the 90's) [4].

## 2. Materials and methods

The research was carried out in the Institute of Production Engineering at the Cracow University of Technology. As machined material the composite consist of aluminium alloy (AA6351) matrix and 15% silicon carbide (SiC) reinforcement was investigated. The bulk material was produced by the stir casting method. The mean grain size is 50  $\mu\text{m}$  and composite porosity is about 5%. The SiC reinforced MMCs have high strength (also in high temperatures), high stiffness and low density, high thermal conductivity and excellent abrasion resistance. Therefore Al-SiC parts are used in high demanding

application (i.e. pistons, pushrods, brake rotors and components) [4].

The machining was carried out in kinematics of milling (Fig. 1) on the EDM prototype machine tool (detailed description in [6]). The purpose of the test was: (i) to determine the EDM machinability with the application of deionized water as dielectric liquid and (ii) to determine the influence of electrical machining parameters on the selected technological factors and surface layer quality. During the primary test the appropriate workpiece polarity was also determined and the workpiece normal polarity (+) was selected. The main part of the research consists of fifteen tests according to the tree level Box-Benhaken research plan. Each test consists of eight passes of an electrode with a nominal layer thickness of 25  $\mu\text{m}$  (Fig. 1). The research conditions, input and factors were listed in Table 1.

After machining, the depth and width of each groove were measured on the Talysurf profilometer (tip diameter 20  $\mu\text{m}$ ). It allows to calculating the volume of removed material and material removal rate. The machined surface roughness was measured with Taylor Hobson Surtronic 25 (example of groove and roughness profile was presented in Fig 2). Additionally based on SEM photographs of each surface a qualitative evaluation of the obtained results was presented.

Table 1. Machining conditions and output factors.

Stable machining conditions	
Workpiece material	(AA6351)-(SiC, 15%) composite
Electrode tool	copper, $d=2\text{ mm}$
Dielectric fluid	deionized water
Pulse-off time	100 $\mu\text{s}$
Number of machined layers	8
Nominal layer depth (a)	25 $\mu\text{m}$
Length of groove (L)	15 mm
Investigated factors	
Pulse-on time $t_i$ [ $\mu\text{s}$ ]	10, 100, 200
Current amplitude I [A]	2.15, 3.45, 5.00
Working voltage U [V]	10, 20, 30
Output factors	
roughness (Ra, Rz); material removal rate (MRR), working electrode wear $W_{\text{VER}}$ (average electrode shortening per layer);	

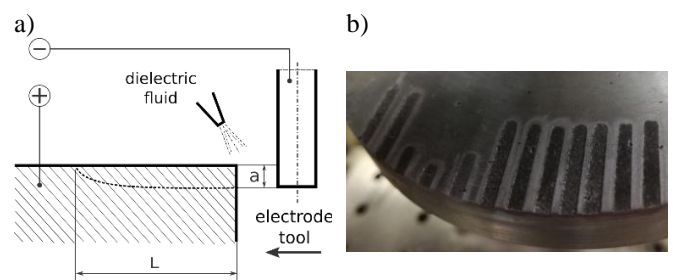


Fig. 1. Scheme of investigated machining variant (a) and photography of the machined sample with groves (b); a – layer depth; the electrode does not rotate during machining.

### 3. Results discussion

The research was performed according to the theory of the experiment and as a response surface full quadratic (constant, linear, interaction, and squared terms) polynomial was selected. To calculate polynomial coefficients and perform regression analysis the Matlab software was used. From obtained relations result that the milling speed  $v$  mainly depends on the current amplitude and working voltage (Fig. 3) and vary from 1000 to almost 4000  $\mu\text{m}/\text{min}$  (it increases with current amplitude). The above-mentioned relation does not correspond with the relation for material removal rate MRR (Fig. 4). MRR increases with current amplitude only for  $U > 20\text{ V}$ ; for  $U$  in range 10 - 20 V and  $I$  in range 3 - 5 A MRR reaches some plateau and does not change significantly. It results from electrode wear, which has maximal values for these window of parameters (Fig. 5). It is worth to mention that during the test the electrode wear was not compensated, therefore groove depth varies from 60  $\mu\text{m}$  to 250  $\mu\text{m}$ ; the width of the groove vary from 2060  $\mu\text{m}$  to 2280  $\mu\text{m}$ , what taking into account diameter of electrode tool  $d = 2\text{ mm}$  allows to estimate side gap width from 30  $\mu\text{m}$  to 140  $\mu\text{m}$ .

From the analysis of cross section profiles one can state, that the width of machined groove decreases with its depth (depending on machining parameters this difference is from 0.02 mm to 0.25 mm). It results from lateral electrode-tool wear. Therefore, on the side walls marks of transition between subsequent layers are also visible (1 on Fig 2a). What is also important, on the groove edges some burrs resulting from melted and solidified alumina matrix occurs (2 on Fig 2a). Its height is in a range of 10 to 20  $\mu\text{m}$ .

In analyzed case, deionized water was applied as working fluid therefore for some range of parameters the electrodischarge erosion is accompanied by electrochemical dissolution (the deionized water can be treated as weak electrolyte). For some range of machining parameters the material is removed by simultaneous interaction of electrochemical dissolution and electrical discharges on the workpiece surface.

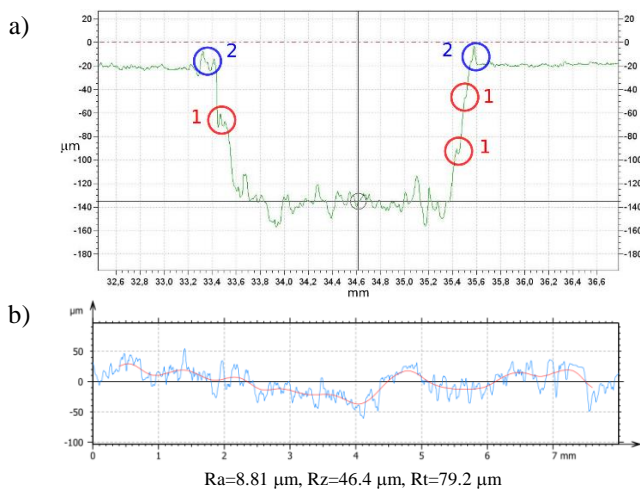


Fig. 2. Example of groove cross-section profile (a) and machined surface profile (1 - transition between layers, 2 – burrs on the groove edge) (b); machining parameters:  $I = 3.45\text{ A}$ ,  $U = 10\text{ V}$ ,  $t_i = 200\ \mu\text{s}$ .

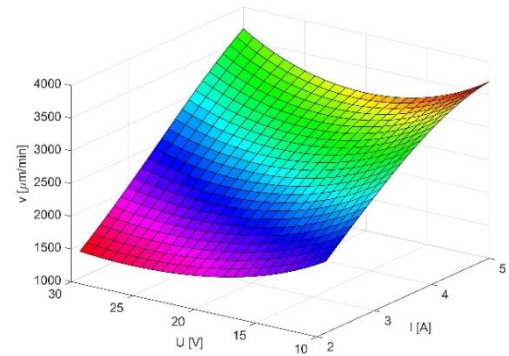


Fig. 3. Relationship between milling speed  $v$ , current amplitude  $I$  and discharge voltage  $U$ ,  $t_i = 100\ \mu\text{s}$ .

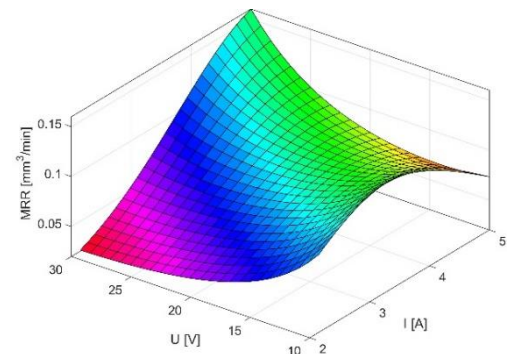


Fig. 4. Relationship between material removal rate MRR, current amplitude  $I$  and discharge voltage  $U$ ,  $t_i = 100\ \mu\text{s}$ .

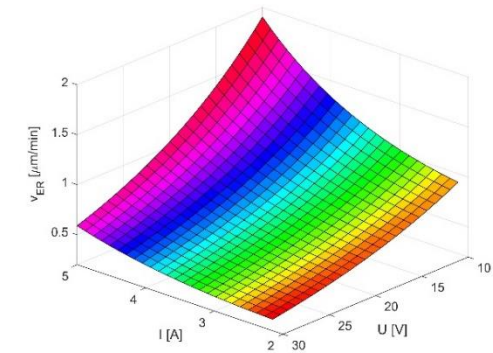


Fig. 5. Relationship between electrode wear speed  $v_{ER}$  (calculated as mean electrode shortening in time), current amplitude  $I$  and discharge voltage  $U$ ,  $t_i = 100\ \mu\text{s}$ .

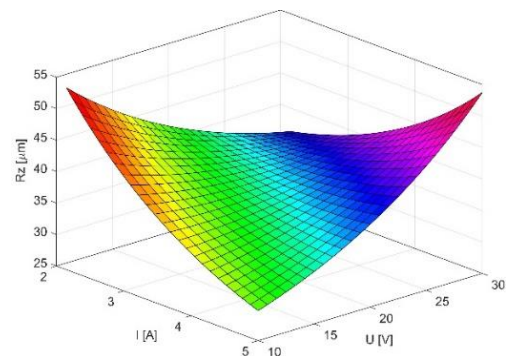


Fig. 6. Relationship between surface roughness  $Rz$  and current amplitude  $I$  and discharge voltage  $U$ ,  $t_i = 100\ \mu\text{s}$ .

Especially, when pulse energy is low, the electrochemical removal component takes an important part in material removal, what cause that SiC grains more easily detach and flows out from the machining area. It influences surface integrity and affects the relationship between surface roughness and machining parameters. Presented in Fig. 6 relationship  $Rz(I, U)$  and SEM photographs (figures 7 and 8) suggests, that the machining process is carried out with different material removal mechanism. For  $I < 3.5$  A the electrochemical process plays an important role. The share of discharges in the removal process is directly connected with the intensity of the electrochemical reaction. When the current amplitude and voltage is low machining conditions allow to easily detach and flush away the SiC grains from the machined surface, therefore surface roughness increases with voltage decrease. While for  $I > 3.5$  A the passing current heats the water much faster and there is no time to obtain effective dissolution. The result is a decrease in the gap thickness and the material is removed in a typical way for the EDM process - the dominant material removal mechanism is melting, evaporating and in some cases also spalling.

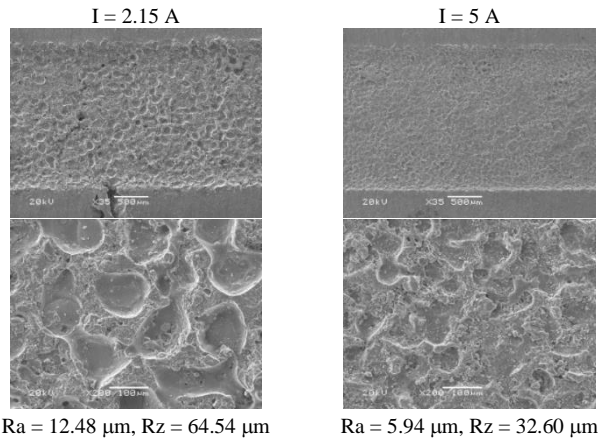


Fig. 7. The SEM photographs of Al-SiC surface after machining with two different current amplitudes ( $I=2.15$  A and  $I=5$  A),  $U = 30$  V,  $t_i=10$   $\mu\text{s}$ .

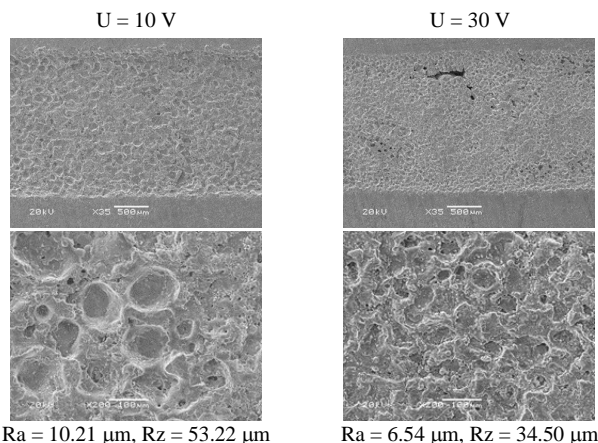


Fig. 8. The SEM photographs of Al-SiC surface after machining with two different working voltage ( $U=10$  V and  $U=30$  Vs),  $I = 2.15$  V,  $t_i=100$   $\mu\text{s}$ .

The contribution of melting in material removal increases with voltage and current increase (amount of droplets on the

surface), however to determine the quantitative share of both actions father research are needed.

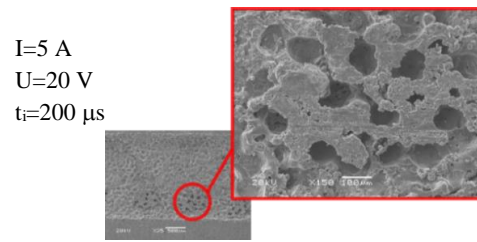


Fig. 9. SEM photographs of Al-SiC surface after EDM with surface defects results from abrasive interaction between workpiece and electrode-tool.

The presented in Fig. 6 relation  $Rz(I, U)$  does not correspond with typical EDM characteristic (increase of  $I$  and  $U$  cause increase of discharge energy, crater size and roughness). Due to above described mechanism, heterogeneity of machined material impact significantly on surface integrity. Also reliability of the investigated process depends on the quality of machined material. Especially volume uniformity of reinforcement grains and unwonted porosity of structure cause problems for automatic gap regulation system. In some cases contact between electrode-tool and machined surface take place and mechanical (abrasive) interaction and surface defects occurs (Fig. 9).

#### 4. Conclusions

The paper presents an experimental investigation of the electrodischarge milling of Al-SiC composite. The experiment involves the impact of machining parameters such as current amplitude, discharge voltage and pulse time on the machining speed and accuracy, tool wear and surface roughness. The analysis between the input and output data shows that the current amplitude and the discharge voltage are the main input parameters that affects the machining efficiency. Due to the application of deionized water as electrolyte, electrochemical dissolution plays an important role in material removal. The obtained results prove that it is possible to machine effectively of MMCs with SiC reinforcement, however farther studies on process adaptation are needed.

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