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Investigation on the effect of copper tool's grain refinement on surface finish in EDM processing

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Abstract. Electrical discharge machining is a modern machining method. With the ever-increasing industrial developments, much research is conducted to improve the output parameters of this process. Meanwhile, previous studies have considered changing the structure and properties of the machining tool materials through different methods as an approach to improve such parameters. The extrusion process or the equal channel angular pressing is a new and efficient method for the production of fine-grained high-strength materials with desirable mechanical and physical properties which can also be used as a new method to improve machining conditions. This study investigated the effect of extruding the electrical discharge machining tool through this method on the output parameter of workpiece surface finish. The machining tool was made of pure copper, and the extrusion process was performed in four and eight stages. Grain size was determined using EBSD. Tool conditions, spark current, and pulse on-time were considered as variable parameters, each of which was changed in three levels. Test results showed that extruding the copper tools reduced the workpiece surface finish quality by 14.1%.

Keywords: Pure copper, ECAP, EBSD, surface finish

1. INTRODUCTION

With the advancement of science and industry, the past hundred years can be considered a part of the history experiencing fundamental and huge industrial changes. In this period, different approaches with their own features have emerged for material shaping and manufacturing. During this evolution, production quality and precision have always been regarded as two major factors with a role in making these methods applicable. Electrical discharge machining or spark machining is one of these modern and non-traditional machining methods. This method was first efficiently used in 1943. Electrical discharge machining is currently very popular in various industries due to its unique features including independence of workpiece rigidity, applying no mechanical force for material removal, and the ability to produce complex shapes with high precision.

In electrical discharge machining, both the tool and the workpiece are electrical conductors and are located in a dielectric material with a specific distance, and both are connected to an electrical pole. After increasing the electrical potential difference between the tool and the workpiece to a certain amount, the dielectric breaks and turns into a conductive material. Since the dielectric material becomes conductive, a spark is generated at the lowest distance between the workpiece and tool. The electrical energy then converts into heat energy and particles of the workpiece melt, evaporate, and are ultimately removed. By continuing the process, an image of the tool is created on the workpiece.

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As mentioned before, the precision parameter in the production, which is addressed by the surface finish, is very important in spark machining, so that improving this parameter can improve the conditions and applications of this material removal method. Various studies have been conducted in this respect. Zhang *et al.* (2014) studied the effect of five different types of dielectric material on material removal rate. It was concluded that the material removal efficiency in liquid dielectrics is greater than gaseous dielectrics. Increase in the pressure at the top of the electrical discharge also improved the material removal efficiency which improved the surface finish [1]. Dalamin *et al.* (2013) investigated the effect of workpiece surface finish on the spark machining process in cases of copper tool and a copper-tantalum carbide compound tool through the powder metallurgy method. The results showed an increase in surface roughness when the copper-tantalum carbide tool was used. They also found that when the copper tool is used, workpiece surface roughness only depends on the current and the pulse on-time [2]. Barman (2013) optimized the surface finish and material removal rate in the spark machining by a pure copper tool though considering current, pulse on-time, pulse off-time, and voltage as variable parameters. Their results showed that current had the greatest impact on the surface finish [3].

Severe plastic deformation (SPD) processes are a group of processes where severe strain is induced in the material without changing the overall dimensions. This process allows for producing materials with very fine grain structure. The equal channel angular pressing (ECAP) method is a new method used for the production of ultra-fine-grained structures with high strength and favorable mechanical and physical properties. In this process, the specimen passes a die which has a channel with a specific angle of curvature. During the passage of material from the curvature of the mold, high shear strain occurs in the material. Since the cross section remains constant and the strain is stored within the material, grain boundaries change and the material becomes fine-grained [4-9]. In a study by Graiger *et al.* (2009) on the microstructure of copper after the ECAP process, it was observed that the average copper grain size changed from the initial value of 50 μm to 5 μm after eight ECAP passes [10].

Based on the stated, tool production using the ECAP method leads to changes in its microstructure and physical and mechanical properties; therefore, it can be investigated as a new method to improve workpiece surface finish parameters in the electrical discharge machining process.

In this research, as the electrical discharge machining tool, pure copper was processed by four and eight passes of ECAP. After determining the average grain size of the specimens using the electron backscatter diffraction method (EBSD), the effect of their use, as an alternative to simple pure copper tool, was examined though a defined set of tests. Tool type, spark current, and pulse on-time were considered variable parameters, each of which was changed at three different levels.

2. MATERIALS AND METHODS

2.1 ECAP Die Selection

Since this study did not focus on the ECAP process, prefabricated ECAP dies were used for processing the copper specimens. Figure 1 shows a schematic of the die used in this study.

The die was made of cold-worked X 153 Cr Mo V12 steel manufactured with DIN 1.2379 standard. The punch was made of Spika Steel (SPK). The die impact angle was 120 degrees, and the outer corner angle was 20 degrees with a channel of circular cross section with a diameter of 10 mm and a length of 160 mm. With regard to the dimensions, it is known that the required copper specimens should be 10 mm diameter bars.

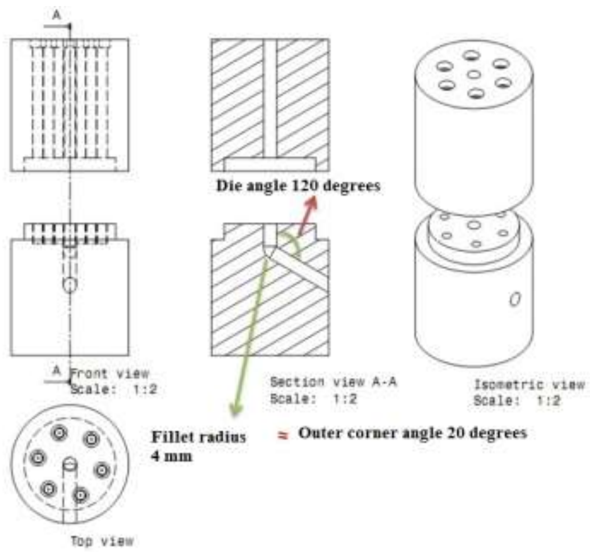

Figure 1. A schematic of the ECAP die used in this study.

2.2 Preparation of pure copper and heat treatment

Bars with a diameter of 10 mm and nominal purity of 99.90% were obtained. Copper bars were manufactured using the cold-rolling process. The cold work and stretch results in the accumulation of residual stresses. These stresses change the crystal structure, strength and properties of copper; therefore, tensile test was conducted to examine the copper material, where yield strength of 245 MPa and an ultimate tensile strength of 373 MPa were measured for the copper.

Results showed that the specimen undergoes brittle fracture. Its strength was also increased compared to the simple copper structure due to the cold work carried out on the specimen during the generation and storage of residual stresses. ECAP induces a strong mechanical work in the specimen at each stage, and if the specimen has high strength, the die can be damaged with increased number of ECAP passes. On the other hand, the purpose of this study was to experiment on pure copper with its initial structure. Therefore, to make the copper structure uniform and eliminate the stored residual stress, the specimens underwent heat treatment through the annealing process. The annealing heat treatment cycle to achieve the most fine-grained and coarse-grained pure copper structures was determined though research. For this purpose, the specimen had to undergo heat treatment for 90 minutes at a temperature of 650 °C and then be cooled in the furnace [11]. An image of the heat treatment furnace used in this study is shown in Figure 2.

Figure 2. The VAS furnace is made in France and, with its graphite elements, allows for heat treatment under vacuum up to 10^{-2} Torr and up to 1500 °C. It has a controlled and programmable heating cycle.

Figure 3. Due to the use of vacuum furnace, the specimen surface was not oxidized with any impurity.

2.3 ECAP Process

At this stage of the research, the aim was to perform the equal channel angular pressing process with two, four, six, eight, and ten passes on the copper specimen so that after examining the crystal structure and grain size, the number of ECAP passes on the main specimens is determined for the electrical discharge machining.

In the ECAP process, specimens are pressed into the die channel and then are removed from the die after passing the channel. A 100 ton hydraulic press was used in order to press the specimens into the ECAP die.

Figure 4. The copper specimen is removed from the ECAP die

2.4 EBSD test

Electron backscatter diffraction is a method of identification of crystallographic directions, material textures, crystalline lattice, defects and grain boundaries, phase, etc. determined by other methods in the past. In this method, an EBSD detector is installed on the SEM device. Once the incident electron beam reaches the specimen, the returning electrons hit a fluorescent phosphor screen and create a pattern on it. The reason for the creation of such pattern is the difference in the intensity of the electrons leaving the specimens due to the changes in its direction. This pattern is known as diffraction pattern whose appearance is associated with the crystal structure of the studied point. EBSD test results of the specimens are shown in Figures 5 and 6.

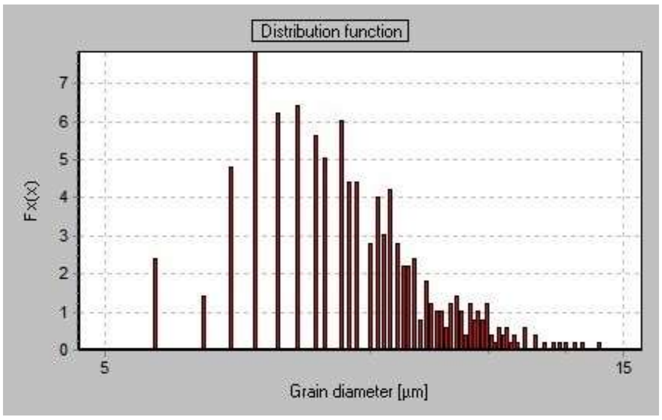

Figure 5. Frequency distribution of grain diameters of the specimen processed with 4 passes of ECAP; Results were obtained using EBSD

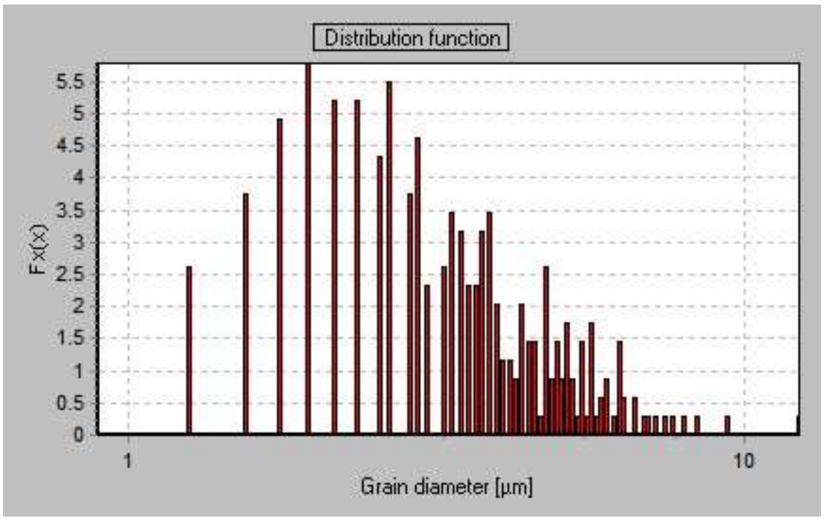

Figure 6. Frequency distribution of grain diameters of the specimen processed with 4 passes of ECAP; Results were obtained using EBSD

Considering the grain size values obtained for the specimens that were processed by four and eight ECAP passes, their graining was suitable for electrical discharge machining tests; therefore, there was no need to test other specimens. Accordingly, in the machining process, simple specimen and the specimens that was processed by four and eight passes of ECAP were considered as variable parameters for the tool.

2.5 EDM Process

Machining tests while considering variable parameters were performed to investigate the effect of fine-grained copper tool processed by ECAP on the workpiece surface finish in the electrical discharge machining process in different working conditions. A variable parameter, which was also studied in this research, is the machining tool. As mentioned before, simple tool or the tool that had not been processed by ECAP was compared with those that had been processed by four and eight passes of ECAP. In this way, three experiment variables are specified.

Machining parameters are another group of variables that can affect the tests. Spark current, pulse on-time, pulse off-time, and voltage spark are the major machining parameters that influence the workpiece surface finish. The literature shows that among the parameters mentioned, spark current and pulse on-time (spark duration) have the greatest impact on the material removal rate and workpiece surface finish [12,13]. Accordingly, spark current (seven, eleven and fifteen amperes) and pulse on-time (one hundred, two hundred and three hundred microseconds) were selected as the variable parameters of machining. Each variable parameter was changed at three levels after a series of initial tests.

Tool in three different conditions of without ECAP, four passes of ECAP, and eight passes of ECAP

Spark current in three levels of 7 A, 11 A, and 15 A)

Pulse on-time in three levels of 100, 200, and 300 μs

In the electrical discharge machining test, Mo 40 steel (DIN 1.7225) was selected as the workpiece material. Mo 40 is one of the most widely-used and heat treatable steel alloys which is popular in many industries, including automotive, aviation and molding.

Figure 7. The EDM 204 device (Ekram Co., Tehran, Iran)

Figure 8. Workpiece and the tool installed and ready for machining

2.6 Workpiece surface roughness measurement after spark experiment

In this study, surface roughness was calculated and obtained based on a common and applicable criterion known as average surface roughness, R_a (center line and average). Marsurf M300 C device (Mahr, Germany) was used to measure the surface roughness values. This device is one of the newest and most accurate systems available in Iran.

At first, due to the geometry of the machined workpieces (the surface under study was the bottom of a hole with a diameter of ten millimeters in a five-millimeter depth of a cube), the probe of the surface roughness measuring device was not able to move on the surface, and the surface roughness measurements were not possible. To solve this problem, all the pieces were cut from the beginning of the curvature of the hole (in the longitudinal direction of the holes) so that the probe could move on the bottom of the hole. Figure 9 shows one of the pieces while its surface roughness is being measured.

Figure 9. Surface roughness measurement using the Mahr device

3. RESULTS AND DISCUSSIONS

Results shown in the diagrams below evidently indicate an increased workpiece surface roughness due to the use of the copper tools processed by ECAP. The ECAP process on the copper tools changes the microstructure (average grain size) and physical and mechanical properties of copper, such as electrical conductivity (electrical conductivity test results showed that ECAP process with up to eight passes increased the electrical conductivity by about 3.1%). This increases the share of energy transferred to the workpiece which in turn increases the size and volume of the holes in the workpiece surface in each spark, which, consequently, increases the surface roughness and reduces the surface finish quality [4,7,10,14].

In all the stages of the test, the use of the copper tool that was processed by ECAP for 8 passes increased the surface roughness compared to the cases where the copper tool with four passes of ECAP were used. In different test conditions, when a copper tool with four passes of ECAP was replaced by a simple copper tool, surface roughness increased by 2-11%. Replacement of the copper tool with four passes of ECAP with the one with eight passes of ECAP increased surface roughness by 0.6-5.3%. These values indicated a reduction in the surface roughness by replacing the copper tool with four passes of ECAP with the one with eight passes of ECAP.

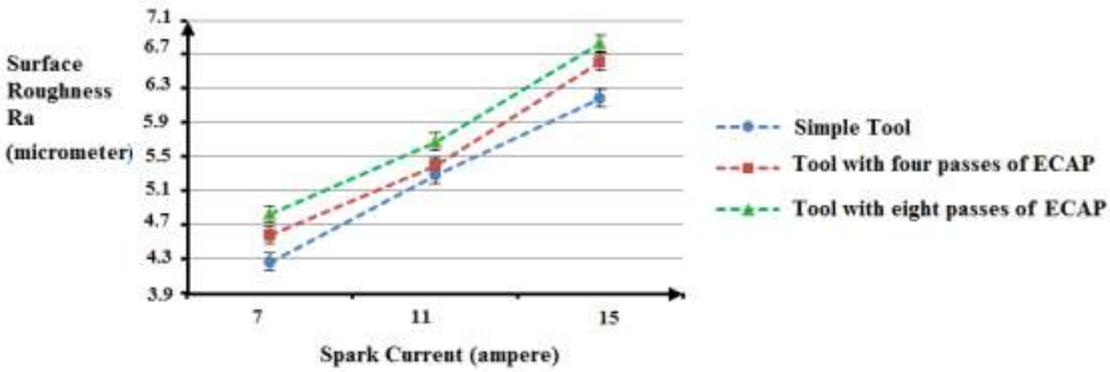

Figure 10. Surface roughness diagrams versus current for the three different tools in the pulse on-time of 100 µs

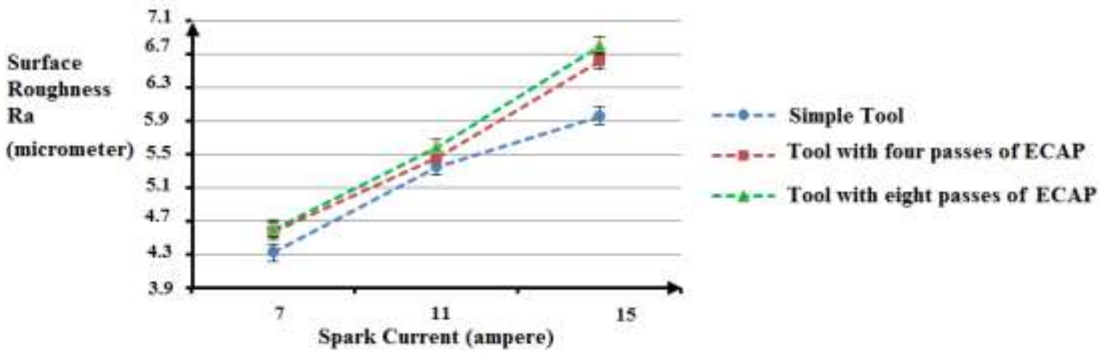

Figure 11. Surface roughness diagrams versus current for the three different tools in the pulse on-time of 200 µs

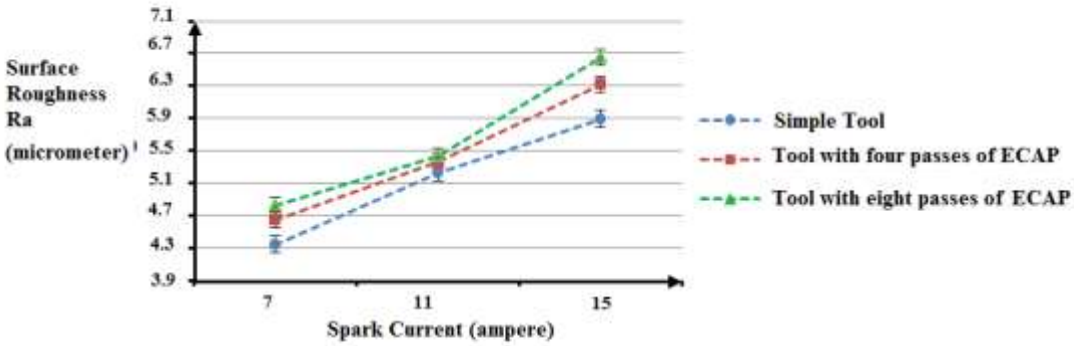

Figure 12. Surface roughness diagrams versus current for the three different tools in the pulse on-time of 300 µs

4. CONCLUSION

This research processed copper with ECAP to investigate the effects of using fine-grained copper on material removal rate in the spark machining process. The pieces that had been processed by ECAP were used as the spark machining tool. The surface roughness of the workpieces was then investigated. The results are summarized as follows:

- The use of the tools processed by ECAP reduced the quality of the workpiece surface finish. In different testing conditions, replacement of the copper tool that was processed by four passes of ECAP with the simple copper increased the surface roughness by 2-11%. Moreover, replacement of the copper tool processed by four passes of ECAP with the one processed by eight passes of ECAP increased the surface roughness by 0.6-5.3%.
- An increased spark current increased the material removal rate and, consequently, created deeper holes in the workpiece which remarkably reduced the quality of the surface finish.
- Increased pulse on-time duration reduced the focus of much of the spark energy on the workpiece due to the dominance of physical factors such as the expansion of the plasma channel. This reduced the material removal rate and, consequently, increased the quality of surface finish.

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