Investigating the Effect of Electrical Discharge Process Input Parameters on Mechanical Properties of Aluminum Surface

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Abstract: One of the important parameters in electrical discharge machining is the presence of micro cracks on the workpiece surface (recast layer). Therefore, the aim of this study was to investigate the possibility of increasing the mechanical properties of aluminum surface by alloying elements (copper and nickel) diffusion to the recast layer and thus removing surface micro cracks. For this purpose, pulse on time and pulse current in with and without ultrasonic vibration have been considered as input parameters and the presence of surface micro cracks has been investigated using microscopic images. Also, the yield stress of the surface layer was calculated using the surface micro hardness. Based on the obtain results, surface without micro cracks has been created on the aluminum surface due to the diffusion of copper and nickel into the workpiece surface which increased aluminum surface yield strength from 90MPa to 280MPa without ultrasonic vibrations and to 310MPa while applying ultrasonic vibrations. In other words, ultrasonic vibrations cause an average of 20% increase in surface layer yield strength. In addition, according to the wear test, in the case of using ultrasonic vibration, improving the mechanical properties of the surface has caused thinner grooves on the aluminum surface.

Keywords: Aluminum, Micro Cracks, Electrical Discharge Process, Surface Yield Strength

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1 INTRODUCTION

Aluminum and its alloys are widely used in the automotive and aerospace industries. Aluminum features include good ductility, high electrical and thermal conductivity, and low weight. The most obvious disadvantages of aluminium (1000 series) are low hardness, low abrasion resistance and low mechanical strength. Thus to increase the mechanical properties of aluminum, especially surface alloying, copper, titanium, chromium, cobalt, nickel and iron are used [1]. The Electrical Discharge Machining (EDM) process is one of the most important and effective methods in machining complex parts. Due to the pulsating nature of the current and voltage in this process, when a current is cut off due to a rapid drop in pressure in the plasma channel and thermal runaway, a small percentage of the melt volume is thrown out of the melt craters and the residue is solidified again. The solidified materials on the workpiece surface that is difficult to etch is called the recast layer (white layer). The distinctive feature of the white layer in all machined specimens is surface cracks, which mostly continue vertically to the depth of the workpiece surface. After the end of the pulse on time, the molten materials quench very rapidly due to contact with the dielectric fluid and non-equilibrium solidification, resulting in very high thermal stresses in the surface layer [2-3].

So, workpieces produced by the EDM require secondary operations such as surface hardening and coating process. First, it is necessary to place the parts under the removal operation on the recast layer that has low mechanical properties (surface micro cracks, etc.). However, an alternative solution could be to increase the mechanical properties through surface alloying during the EDM, which eliminates the need for secondary operations on the surface of the parts [4]. Quality control and guarantee methods in various industries, especially in aerospace industries, usually require testing of mechanical properties such as tensile testing on samples made of aluminium. Although these tests have accurate results, but the mechanical tests are not only time consuming but also lead to the destruction of the original part in some cases, which in turn, increases production costs. Therefore, non-destructive methods for estimating mechanical properties, especially yield stress (σ_y) and tensile strength have been considered [5].

One of the methods used to estimate the yield stress is the indentation hardness test. This test on the evaluation of surface coating properties, can be performed on real parts with real dimensions and does not require any sample for testing. One of the indentation hardness tests used in industry is Vickers hardness test, which uses a pyramidal indenter to determine the amount of hardness [5]. According to the "Eq. (1)" , the mean pressure applied by the indenter based on the Mayer method, Pm, is the result of the division of the applied load, L, on the surface area of the indenter A_i [5]:

$$P_m = \frac{L}{A_i} \tag{1}$$

The flow stress under the indenter, σ_f, is related to mean pressure [5]:

$$\sigma_f = \frac{P_m}{C} \tag{2}$$

Where, C is a constant value that is considered for most metals as C = 3. Based on the analysis of the stress distribution under a wedge indenter, the pressure applied to the surface can be presented as "Eq. (3)" [5]:

$$P_m = 2\tau_c(1+\theta) \tag{3}$$

Where, τc is the maximum critical shear stress and θ is the angle of the geometric model provided by Hill et al [5]. In the case of flat indenters of the Vickers method, θ is considered to be **π**/2. The relationship between τc and yield stress can be shown by "Eq. (4)" through Haber-Mays criterion such that [5]:

$$2\tau_c = 1.15\sigma_Y \tag{4}$$

Combining Equations (3) and (4) and taking θ=π/2, we obtain:

$$P_m = 1.15\sigma_Y\left(1+\frac{\pi}{2}\right) \tag{5}$$

Therefore,

$$P_m = 2.956\sigma_Y \tag{6}$$

Since flow stress is assumed to be equal to yield stress in these loading conditions, the constant value in "Eqs. (2) and (6)" is approximately C=3. Since Tabor's statement that C ≈ 3, many researchers assumed the mean pressure under an indenter to be three times the tensile yield strength of the metal [5]. In calculating the Vickers hardness, the relationship between the amount of hardness and the mean pressure is (5):

$$H_v = 0.927P_m \tag{7}$$

By placing "Eq. (6)" into "Eq. (7)" , the yield stress can be calculated in terms of the Vickers hardness [5]:

$$\sigma_y = \frac{H_v}{0.927C} \tag{8}$$

Taking C = 2.956, Hv, and σ_y are both in terms of (MPa) [5].

In this paper, "Eq. (8)" is used to calculate the yield stress of surface layer after the electric discharge process.

Most of the research on the surface properties of aluminium has been done using the laser method, which is useful for identifying elements that have the ability to increase the mechanical properties of aluminium surfaces. Jiru et al., [6] studied the surface alloying of pure aluminium by the use of laser method and using copper, manganese and magnesium powder with ratios of 2:1:1, respectively, with the aim of increasing the surface hardness. According to the results of this study, the surface hardness has increased from 30 to 430 Vickers. In addition, Jiro et al. [1] evaluated 99% aluminium surface alloying with copper powder through laser. Their research indicated that after surface alloying, surface hardness increases from an initial value of 60 to 156 Vickers. Mahabali et al. [7] studied the surface alloying of AA1200 aluminum with Ni + SiC powder using laser. According to their results, the hardness of 24 has reached 120 Vickers at the highest level. Lin et al. [8] performed research to improve the surface properties of aluminum using EDM process. They studied the surface alloying of aluminum 5083 with a powder metallurgy electrode (iron + silicon) and introduced this process as a new way to improve surface alloying, which can simultaneously change the mechanical and chemical properties of the aluminum surface. In their research, the applied pulse current and pulse on time are considered as input parameters and thickness of alloyed layer, hardness and surface roughness were considered as output parameters.

Since the maximum surface residual stress caused by the electric discharge process, depends on the strength of material; one of the reasons for the presence of surface cracks in this method is that the tensile strength of workpiece is less than the amount of residual stresses. Therefore, increasing yield stress with selecting the appropriate electrode besides performing the surface alloying process can remove or minimize the surface cracks. Therefore, the aim of this study was to increase the strength of the aluminium surface layer with EDM process by diffusion of copper and nickel to recast layer using the monel electrode as a solid tool without the need to make powder metallurgy electrode. Moreover, the effect of EDM input parameters (pulse on time, pulse current and application of ultrasonic vibrations) on the surface layer yield stress and surface cracks has been investigated.

2 MATERIAL AND METHODS

In performing the experiments, pure aluminum was selected as the workpiece material with the purity of 99.98% and the tool material was selected as Monel 400. In order to prepare the aluminum specimens, the cutting, turning and finishing operations were carried out on the raw material and 16 specimens' cylindrical aluminums with the dimensions of Ø12×14mm^2 were produced. To prepare 16 cylindrical electrodes with the dimensions of Ø18×20mm^2 the cutting, machining and grinding operations were done performed on Monel 400. The chemical composition of aluminium workpieces and Monel 400 electrode are represented in "Tables 1 and 2" respectively, (Elements less than 0.001 %wt are not listed in the tables).

Table 1 Chemical composition of pure aluminum (%wt)

Al	Mn	Fe	NI	Si	Mg	Cr
99.80	0.003	0.118	0.006	0.04	0.003	0.004

Table 2 Chemical composition of Monel 400 (%wt)

Ti	Zr	Al	Cr	Fe	Ni	Cu
0.032	0.035	0.14	0.095	1.65	66.64	28.09

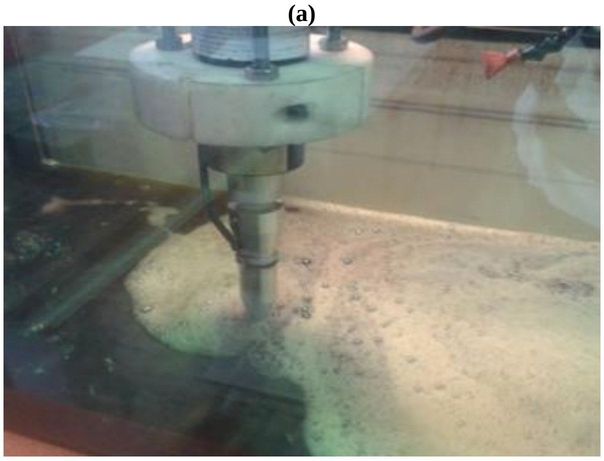
During the experiments, to apply ultrasonic vibrations, an ultrasonic head (200W - 20 kHz) was used. All samples were machined by the use of die sinking EDM machine (CNC- Charmilles Roboform 200) with an iso-pulse generator. Each test was performed for 20 minutes. In order to create the same conditions for flushing during all experiments, the normal submerged flushing method was used. "Table 3" provides input parameters and test conditions.

Table 3 Experimental test conditions

Parameter	Condition
Dielectric fluid	Kerosene oil
Pulse on-time (µs)	50,100,200,400
Voltage(V)	160
Pulse current (A)	12,16,24,32
Pulse of time (µs)	800
Tool Polarity	Negative

The optical microscope (Olympus PMG3) was used to provide microscope images. The hardness of surface layer was measured by using a hardness measuring instrument Olympus LV 700 hardness tester. Therefore, the specimens were sectioned transversely and prepared under a standard procedure for metallographic observation by utilizing Cam Scan MV2300 Scanning Electron Microscopy (SEM). In addition, the samples were tested for wear test to investigate the effect of ultrasonic vibration on the surface properties. The pin on disk method with a linear speed of 10 (cm/s) and a sliding distance of 500 (m) was used by the wear testing machine manufactured by AMI Sanat Company. Figure 1 shows the setting of the electrodes and ultrasonic head to electrical discharge process.

(a)



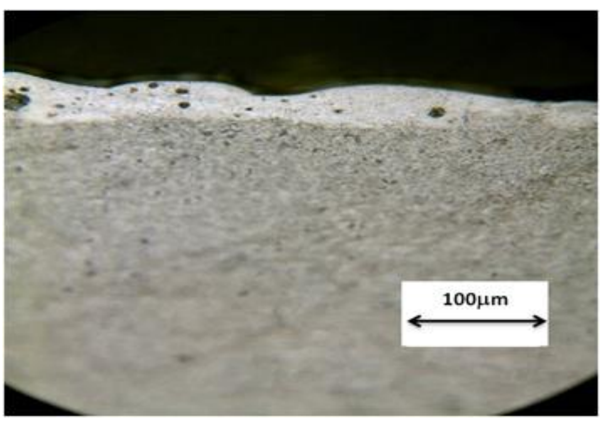
(b)

Fig. 1 Tool and ultrasonic head used in electrical discharge process: (a): Tool and workpiece, and (b): Ultrasonic head.

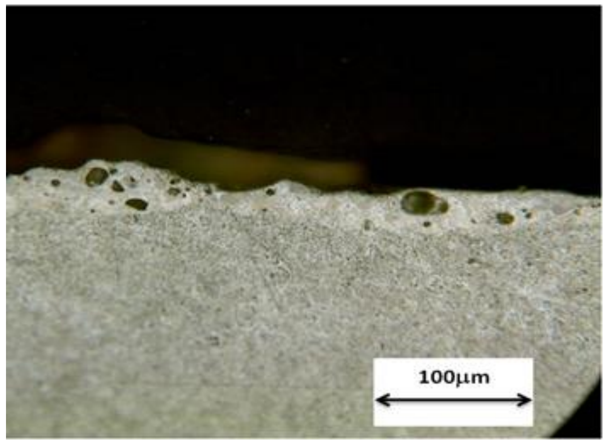
3 RESULTS AND DISCUSSION

3.1. The Effect of Pulse on Time and Pulse Current on Surface Micro Cracks

Figure 2 shows the optical microscope images and "Fig. 3" shows SEM micrograph of the aluminum surface after electric discharge process.

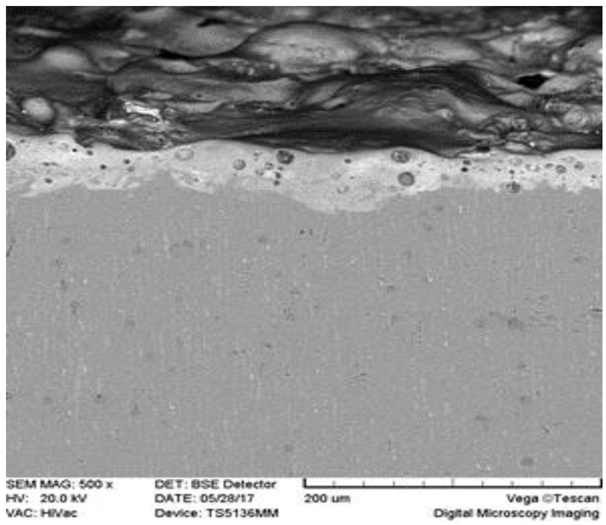


(a)

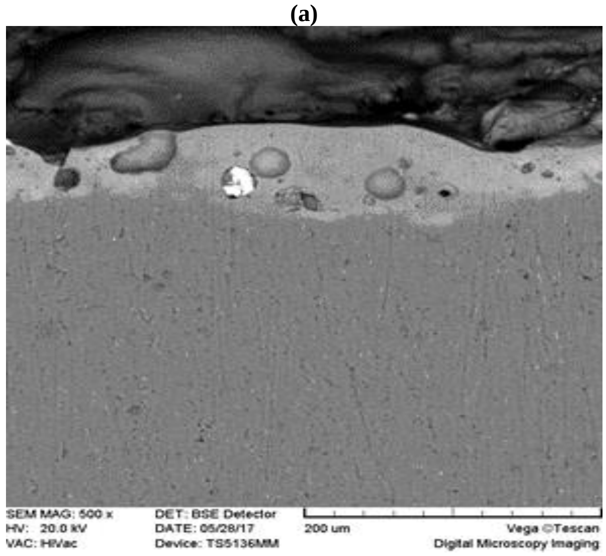


(b)

Fig. 2 Aluminum surface after electrical discharge process: (a): I=32A Ton=100μs, and (b): I=16A Ton=100μs.



(a)



(b)

Fig. 3 SEM micrograph showing cross-section of workpiece: (a): I=24A Ton=100μs, and (b): I=32A Ton=400μs.

According to “Figs. 2 and 3” , no micro crack is observed on the aluminum surface; in other words, the formation of cracks on the workpiece surface is prevented during the electric discharge process. It is reported in the literature that the causes of surface micro cracks in the workpiece surface after electrical discharge process, are thermal stresses and phase’s change, which leads to the creation of surface residual stress in the workpiece surface. The amount of residual stresses created is approximately equal to the ultimate strength of the workpiece, but if the amount of these stresses exceeds the yield strength of the workpiece, it will lead to surface cracks [9-10]. By comparing the initial composition of the aluminum workpiece (“Table 1”) with the EDX analysis of the surface layer after the electrical discharge process (“Fig. 4”), a significant increase in the copper and nickel elements is observed on the workpiece surface (In EDX analysis, the main peak is related to Al and second peak is characterisitic of Cu and Ni). Therefore, the reason for not creating surface cracks can be explained by the fact that by creating sparks, copper and nickel particles diffuse to surface layer and as a result, they have caused the surface alloying of aluminum. These elements increase the mechanical properties of the surface layer so that thermal stresses and residual stresses do not cause micro cracks on the aluminum surface.

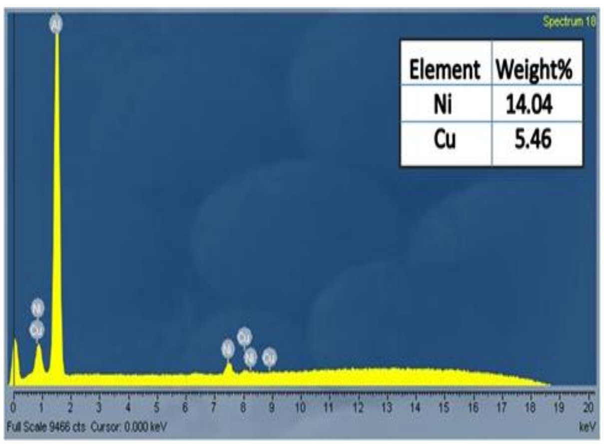


Fig. 4 EDX analysis of surface layer after electrical discharge, process (T_{on}=100s, I=16A).

Figure 5 shows the effect of pulse on time and pulse current on the surface yield stress which is calculated using Equation 8. According to this figure, the diffusion of copper and nickel to the recast layer has increased the strength of the aluminum surface, so that with increasing input parameters, the yield stress of the surface layer has increased. The reason for this can be explained by the results of EDX analysis (Fig. 6). As the pulse on time and pulse current increase, the energy of the sparks increases and with increasing the electric current density, more copper and nickel diffuse to aluminum surface, and as a result, the amount of surface layer yield strength increases [11].

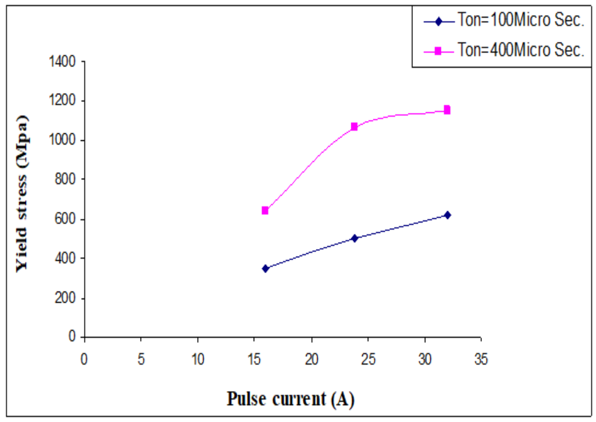
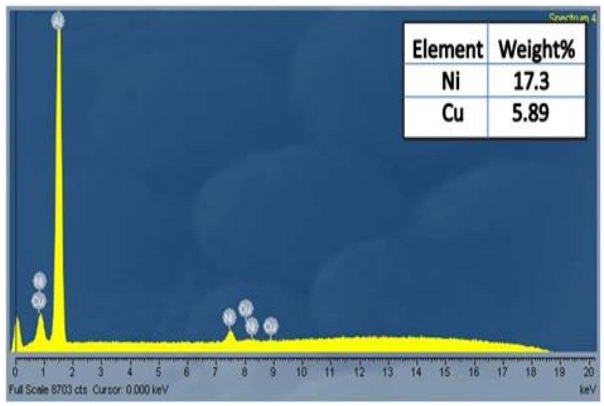
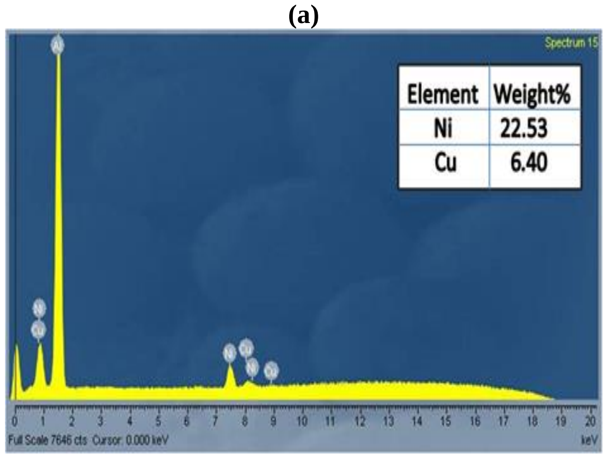


Fig. 5 Effect of electric discharge input parameters on the surface layer yield stress.



(a)



(b)

Fig. 6 EDX analysis of surface layer after electrical discharge process, (a): T_{on} =400µSec, I=24A, (b): T_{on} =400µSec, I=16A.

3.2. The Effect of Tool Ultrasonic Vibrations on the Surface Yield Stress

Figures 7 and 8 show the effect of tool ultrasonic vibrations on the yield stress of the workpiece surface and “Fig. 9” shows the effect of ultrasonic vibrations on the amount of diffusion of copper and nickel into the aluminum surface. As can be seen, with ultrasonic vibrations to Monel tool, the yield strength of the surface layer is increased with an average of 20%. One of the main factors in solid solution hardening is the amount of alloying elements, so that with increasing the amount of alloying element, the hardening effect increases [12], Thus increasing the amount of copper and nickel on the aluminum surface simultaneously with the application of ultrasonic vibrations (“Fig. 9”), can increase the yield strength of the surface layer.

However, the reason for increase in the amount of copper and nickel diffusion in aluminum surface by applying ultrasonic vibrations can be the impact of the Monel electrode with ultrasonic vibrations on particles, which separate them and throw them at molten carter on aluminum surface. Ultrasonic vibrations prevent particles sticking to the Monel electrode, thus increasing the amount of copper and nickel diffusion in aluminum surface [13].

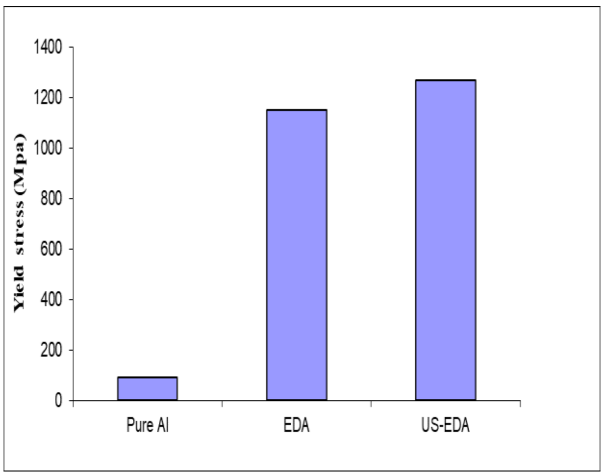


Fig. 7 Effects of ultrasonic vibrations on surface layer yield stress, (T_{on}=400µSec, I=32A).

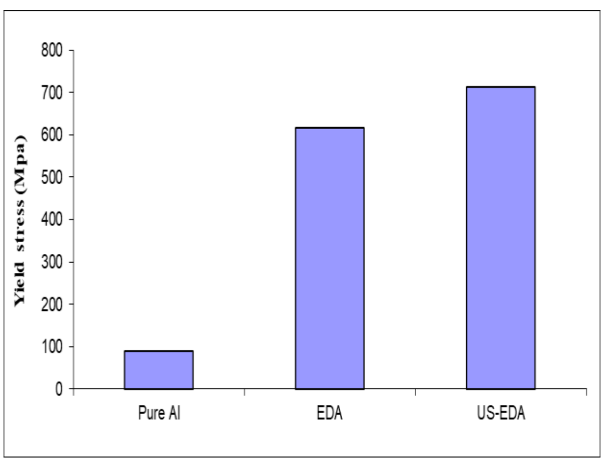
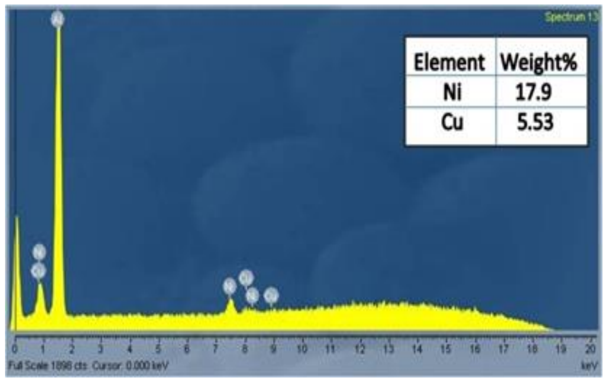
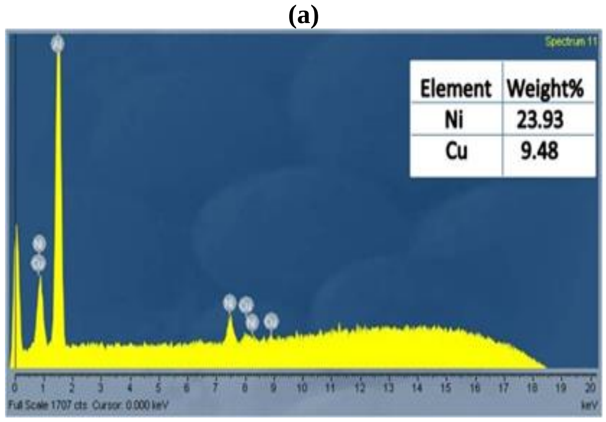


Fig. 8 Effects of ultrasonic vibrations on surface layer yield stress, (Ton=100µSec, I=32A)



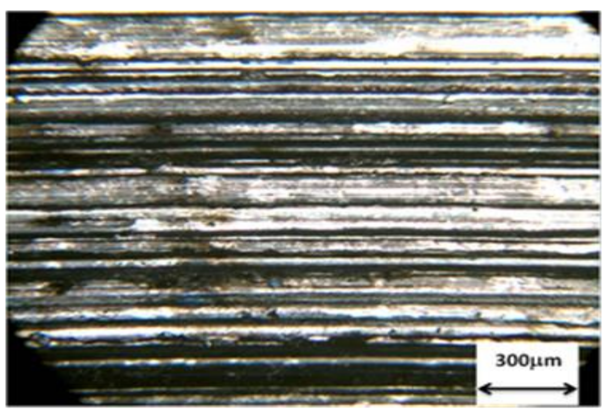
(a)



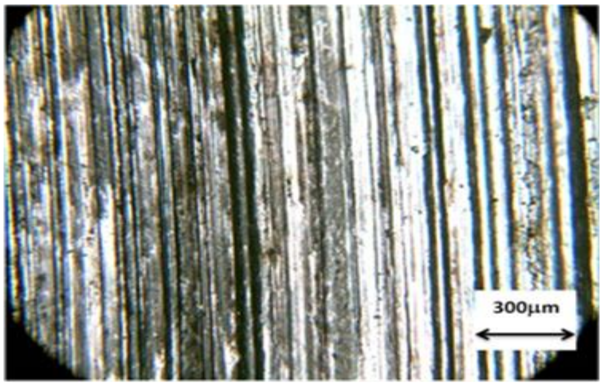
(b)

Fig. 9 EDX analysis of surface layer after electrical discharge process (T_{on}=100µSec, I=32A), (a): Electrical discharge without ultrasonic vibration, (b): Electrical discharge with ultrasonic vibration.

In addition, literature review indicates that the molten metals that is solidified under ultrasonic vibrations have a more uniform and finer microstructure which can increase hardness and strength [14]. The effect of ultrasonic vibration on increasing hardness and strength that in turn, affect the surface wear status of aluminum samples is shown in “Fig 10” . In the case of using ultrasonic vibration, improving the mechanical properties of the surface has caused thinner and narrower grooves on the aluminum surface.



(a)



(b)

Fig. 10 Aluminum surface after wear test, (I=12A, T_{on}=400μs), (a): Electrical discharge without ultrasonic vibration, (b): Electrical discharge with ultrasonic vibration.

4 CONCLUSIONS

In this paper, increasing the yield strength of aluminum workpiece surface in EDM process was investigated using the diffusion of copper and nickel to recast layer and the surface layer yield strength was calculated using micro hardness results. The summary of the results is as follows:

1. The diffusion of alloying elements into the recast layer in the EDM process can prevent the formation of surface micro cracks caused by thermal and residual stresses.
2- As the amount of alloying elements increases in the aluminum surface, the yield strength of the surface layer increases.
3- Ultrasonic vibrations to monel electrode increase the amount of alloying elements diffusion in aluminum surface and increase the surface yield strength compared to non-ultrasonic vibrations mode.
4- With the pulse on time and pulse current increase, the surface layer yield strength increases. Example (these abbreviations are not italicized).

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