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Comparative Study of Ultrasonic Vibrations Assisted EDM and Magnetic Field Assisted EDM Processes

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In this investigation, the material removal rate, tool wear rate and surface integrity obtained by EDM, ultrasonic vibrations assisted EDM and magnetic field assisted EDM were studied and compared with together to show the quality of the effects of applying each of ultrasonic vibrations to tool and magnetic field around gap distance of EDM process on material removal rate, tool wear rate, and surface integrity. According to the results, applying ultrasonic vibrations to tool electrode leads to an increase of 71% in material removal rate of EDM process while applying magnetic fields around gap distance of EDM process leads to an increase of 41% in material removal rate (of course in the best conditions). Also, applying magnetic fields around gap distance of EDM process leads to a decrease of 35% in surface roughness obtained by EDM process while the surface roughness of ultrasonic vibrations assisted EDM is higher than EDM process. Also, the created surface damages in the case of ultrasonic vibrations assisted EDM is the lowest and in the case of EDM process is the highest.

Keywords: Ultrasonic Vibrations Assisted EDM, Magnetic Field Assisted EDM, Material Removal Rate, Tool Wear Rate, Surface Quality

1 Introduction

In the electrical discharge machining (EDM) process, the tool moves to the workpiece until the gap between the tool and the workpiece is sufficiently decreased for dielectric fluid ionization with the applied voltage [1]. With the dielectric fluid ionization at the gap distance, the electrical current between the tool and the workpiece is established within a short time interval [2].
By converting electrical energy into heat energy, the temperature of the plasma channel formed between the tool and the workpiece reaches to 8000-12000°C, which causes melting of the tool and the workpiece. By cutting off the electrical current, the plasma channel is expanded and causes a sudden drop in the temperature of the plasma channel and the jumping of molten material from the surface of the workpiece and tool [3].

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Along with the widespread use of the electrical discharge machining process, this process has some limitations and disadvantages, such as low material removal rate, high tool wear rate, surface roughness and surface cracks, metallurgical changes in the surfaces and sub-surfaces of machined parts, creating heat affected zone, and the recast layer [4, 5]. Therefore, various researchers have introduced new machining methods based on the EDM process, such as ultrasonic vibration assisted EDM (UEDM) [6], powder mixed EDM (PEDM) [7], Magnetic field assisted EDM (MEDM) [8], Dry EDM [9] and the near dry EDM [10] processes, to resolve these constraints. In the ultrasonic vibrations assisted EDM process, the ultrasonic vibrations are applied to tool, workpiece or dielectric fluid to improve the machining performance [11]. The contaminated dielectric fluid by the machining chips is repelled out of the machining gap by moving up the tool. Also the fresh dielectric fluid is sucked and transports to the machining chamber, by moving downwards the tool. As a result of this, the number of abnormal pulses, such as the arc, also the amount of created recast layer on the surface of workpiece and tool is reduced [12]. On the other hand, better removal of produced chips from the gap distance due to the better rotation of the dielectric fluid in the gap distance, and the cavitation phenomenon, due to the ultrasonic vibrations of the workpiece, tools or dielectric fluid, increase the material removal rate of the electrical discharge machining process [12]. Also workpiece, tool or dielectric fluid ultrasonically vibrations can prevent the accumulation of carbon and other particles in the gap distance. So, the occurrence of pulses such as arc and short circuits is reduced by changing the distribution of these particles at the gap distance [12]. In the magnetic field assisted electrical discharge machining process, a magnetic field is applied around the tool, gap, and the workpiece, and the machining is done in this condition. In this process, the material removal rate is increased, the created recast layer on the workpiece surface is reduced and a better surface quality is obtained [13]. By applying the magnetic field around the gap distance in the electrical discharge machining process, a magnetic force is applied to the charged particles presented at the gap distance (electrons and protons), in addition to the electric force generated by the electric field between tool and workpiece. Therefore, the resulting force called Lorentz force is applied to charged particles inside the plasma channel.

Generating Lorentz force reduces the radius of the plasma channel; increases the density of the electrons inside the plasma channel and thus increases the energy density of plasma channel. Plasma channel ionization also increases as a result of increasing the collisions between charged particles due to a decrease in the mean free path of electrons inside plasma channel by limiting their movement due to applying the magnetic field around the gap distance in the EDM process [14, 15]. The application of ultrasonic vibrations of tool and workpieces in the electrical discharge machining process was first proposed by Murthy and Philip in (1987) [16], as well as by Kremer et al. in (1989) [17], to solve the problems and limitations of the electrical discharge machining process and improve the performance of this process [18]. According to the Shervani-Tabar and Shabgard investigation about ultrasonic vibrations assisted EDM process [19], the rate of pressure drops in the bubble and on the workpiece surface is increased by increasing the frequency and amplitude of the ultrasonic vibration of the tool. Shervani-Tabar et al. [20], simulated the bubble behavior that forms between the tool and the workpiece in the electrical discharge machining process with ultrasonic vibrations, numerically.

They also performed some experiments to study the effects of applying ultrasonic vibration to tool on the process performance. The numerical results showed that the volume and life time of the steam bubble reaches to its maximum value, by sparking at the closest point between the tool and the workpiece. Because in this case, the tool is moving away from the workpiece surface during the growth and disappearing of bubbles and that leads to reduce the pressure inside the bubble to its lowest value, which makes the better evaporation and expulsion of the molten materials from workpiece surface (as compared with the state of machining process where the ultrasonic vibrations are applied to the tool in electrical discharge machining process, but the electrical spark occurs between the tool and the workpiece when the tool is away from the workpiece). Gao and Liu [21], investigated the micro electrical discharge machining process with the ultrasonic vibrations of workpiece. They showed that the efficiency of the micro electrical discharge machining, as well as the dimensional accuracy of the machined hole with this process, is improved by applying ultrasonic vibration to the workpiece. Chern et al. [22] developed a new micro-drilling machine based on the electrical discharge machining process, applied ultrasonic vibrations to tool and examined the ultrasonic vibrations assisted micro electrical discharge machining process. They concluded that by applying vibrations to this system, the efficiency of micro electrical discharge machining process is increased, the obtained dimensional accuracy is improved, and the machining time and the probability of the occurrence of abnormal pulses, such as short-circuits, are decreased. Zhao et al. [23], studied the ultrasonic vibrations assisted micro electrical discharge machining process of titanium alloys.

They concluded that applying ultrasonic vibrations in the micro electrical discharge machining process improves the removal of generated chips and pollutions from the gap distance. Zhang et al. [24] studied the ultrasonic vibrations assisted dry electrical discharge machining process and concluded that the material removal rate of process is increased by applying ultrasonic vibrations. According to their results, the main advantage of this combined method is lower environmental pollution and tool wear rate. De Bruijn et al. [25], were the first researchers which applied the magnetic field around the gap distance in the electrical discharge machining process in (1978). Lin and Lee [26], studied the magnetic field assisted electrical discharge machining process. They concluded that, less number of abnormal pulses (such as arcs), more material removal rate (3 times) and less surface roughness is obtained in magnetic field assisted electrical discharge machining process as compared with electrical discharge machining process. Lin et al. [27] compared the electrical discharge machining process and magnetic field assisted electrical discharge machining process. According to their results, the magnetic field assisted electrical discharge machining process leads to better machining stability.

According to the above review of the literature, there are many investigations about applying ultrasonic vibrations to tool and magnetic field around gap distance of EDM process in order to decrease the limitations of EDM process, but there is no any comparison between these two methods. In this study, the material removal rate, tool wear rate, and the surface integrity obtained by the electrical discharge machining, magnetic field assisted electrical discharge machining and ultrasonic vibration assisted electrical discharge machining, were compared with each other to determine the amount and quality of the effects of applying magnetic field around the gap distance and the ultrasonic vibrations to tool in the electrical discharge machining process on material removal rate, tool wear rate, and the surface integrity.

2 Experimental conditions

2.1 Equipments

The Charmilles Roboform 200 CNC Sinker EDM with Iso current pulse generator is used for drilling operations. In this machine, Z-axis is controlled by the servo control mechanism based on the gate voltage and the input parameters of the machine, such as current, pulse on-time, and pulse-off time is controlled by the control panel of the machine.

To apply ultrasonic vibration to the tool, a Bandelin 2200 ultrasonic vibration generator, with a power of 200 watts and a vibration frequency of 20 kHz is used to create ultrasonic waves with an amplitude of 15 microns. The aluminum concentrator is also used to increase the vibration amplitude. Figure (1) show the ultrasonic vibration generator used in this study. Figure (2) also shows the EDM machine along with the ultrasonic vibration generator in the ultrasonic vibrations assisted electrical discharge machining process.

Figure 1 The ultrasonic vibration generator

Figure 2 The spark machine which was used at ultrasonic vibrations assisted EDM

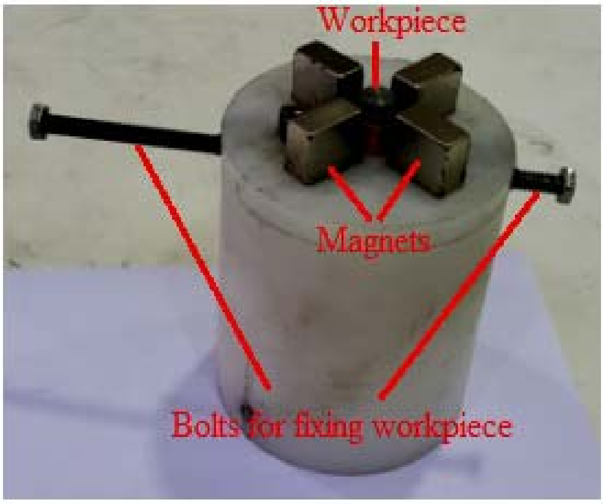

Figure 3 The fixture which was used at magnetic field assisted EDM

The fixture shown in figure (3) is designed for the workpiece, to apply the magnetic field around the gap distance in the electrical discharge machining process. This fixture is made of plastic, with four fixed cubic Neodymium magnets with 1.2 Tesla magnetic intensity and in dimensions of 10 × 20 × 25 mm placed in the vacancies on the fixture body. Neodymium magnet has a much higher magnetic resistivity than other magnets, which has turned it into a permanent magnet with a wide range of applications. The small size and higher power are features that have led to the use of this type of magnet in sensitive tasks with an appropriate function.
It is worth mention that the shape, dimensions, magnitude of magnetic field, the number and positions of the magnets in the magnetic field assisted electrical discharge machining process, were determined according to the exploratory experiments performed before the start of the main tests and taking into account the highest obtained material removal rate as the output parameter [28].

2.2 Experimental procedure

In order to investigate the amount and quality of the effects of applying magnetic field around gap distance and ultrasonic vibrations to tool electrode of EDM process in comparison with each other, on the machining efficiency and machined surfaces integrity, discharge current and pulse on-time each one in 4 level, considered as input parameters. According to the design principles of the experiments and based on the full factorial design model, 16 tests in the electrical discharge machining process, 16 tests in the electrical discharge machining process with the magnetic field and 16 tests in the electrical discharge machining process with ultrasonic vibrations of tool and in total, 48 experiments were designed. These experiments were performed to compare the effects of applying magnetic field around gap distance and ultrasonic vibrations to tool electrode of EDM process in different pulse currents and pulse on-times, on the material removal rate, the tool wear rate and the obtained surface integrity (including the machined surface roughness and the quality of machined surfaces) as output parameters of these processes. constant parameters of the tests and also variable input parameters levels in the electrical discharge machining process, electrical discharge machining with the magnetic field and the electrical discharge machining with the ultrasonic vibration of the tool, as same as each other, are accordance with table (1).

In this research, one tool electrode was used to perform each test and the time of each experiment was fixed (10 minutes).

To calculate the material removal rate and the tool wear rate, the workpiece and tool are completely cleaned, then weigh with the digital balance of Sartorius CP224S with a precision of 0.0001 grams before and after each test.

In the following, the material removal rate and the tool wear rate are calculated by using equation 1 and 2.

$$MRR = \left(\frac{M_{W1}-M_{W2}}{\rho_w t}\right) \times 10^6 \tag{1}$$

In equation 1, MRR is the material removal rate, M_{W1} is the weight of the workpiece before machining, M_{W2} is the weight of the workpiece after machining, t is the machining time and ρ_W is the workpiece density.

$$TWR = \left(\frac{M_{T1}-M_{T2}}{\rho_T t}\right) \times 10^6 \tag{2}$$

Table 1 Variable fixed input parameters with their levels

Current (A)	4, 8, 16, 32
Pulse on-time (µs)	6.4, 12.8, 50, 100
Pulse-off time (µs)	6.4
Open circuit voltage (V)	200
Gap distance (µm)	50
dielectric	Oil Flux ELF
polarity	positive

In the equation 2, TWR is the tool wear rate, M_{T1} is the tool weight before machining, M_{T2} is the tool weight after machining, t is the machining time and ρ_T is the tool density.

The roughness of machined surfaces is measured by Mahr surface roughness measurement, with a probe movement of 5.6 mm on the samples surface and standard length of 0.8. In this study, the average surface roughness (Ra) is considered as the surface roughness criterion. To increase the accuracy, the machined surface roughness is measured in five different directions and the mean roughness is considered as the final surface roughness.

In order to check the quality of the machined surfaces, some images from the surface of machined parts were captured using a field emission scanning electron microscopy (FESEM).

2.3 Tools and workpiece materials

The AISI H13 hot work tool steel has a high tensile strength (1400-1750 N / mm^2). High toughness and resistance against abrasion, thermal cracking, fatigue, corrosion, oxidation, and chemical interactions are the most important properties of this steel. In this steel, hardness is maintained up to 425°C, and the tools made from this material also can be used up to high temperatures (540°C).

Table (2) shows some of the physical, mechanical and thermal properties of H13 steel. The workpiece used in this study is a 10 mm diameter and 20 mm in height AISI hot work H13 cylindrical steel, with grinded and polished surface. The chemical composition of the workpiece, which is electrically conductive and has magnetic properties, is given in table (3).

Table 2 The physical, mechanical and thermal properties of H13 tool steel

parameter	**quantity**
Density in 20°C	7.80
Melting point	1427
Ultimate tensile strength (MPa) in 20°C	1200-1590
Yield stress (MPa)	1000-1380
Elastic modulus (Gpa) in 20°C	215
thermal conductivity (W/Mk)	28.6

Table 3 Chemical composition of H13 tool steel

element	Wt%	element	Wt%
Fe	91.73	Mn	0.4
Cr	5.2	V	1.1
C	0.39	Cu	0.25
Si	0.9	S	0.03

The cylindrical tool material used in this study is copper in 99% purity, with a diameter of 14 mm and a height of 40 mm. In the electrical discharge machining process with ultrasonic vibrations of the tool, the end of tools was threaded, in order to connect the copper tool to a special ultrasonic head.

3 Results and Discussion

3.1 Material removal rate

Figure (4) illustrates the effects of pulse current on material removal rate of electrical discharge machining processes, electrical discharge machining with magnetic field and electrical discharge machining along with ultrasonic vibrations of the tool. As shown in figure (4), the material removal rate of electrical discharge machining processes, electrical discharge machining along with the magnetic field and the electrical discharge machining with the ultrasonic vibration of the tool, is increased with increasing discharge current, at all pulse on-times. The amount of melted material and thus the material removal rate is increased with increasing discharge current from 4 A to 32 A, due to increasing the amount of delivered energy to the gap distance and increasing the amount of heat generated on the workpiece surface (according to equation 3). This phenomenon was observed at all pulse on-times.

$$Q = R \times I^2 \times T_{on} \tag{3}$$

In equation 3, Q is the generated heat, R is the electrical resistance between the tool and the workpiece, I is the amount of discharge current, and T_{on} is the pulse on-time.

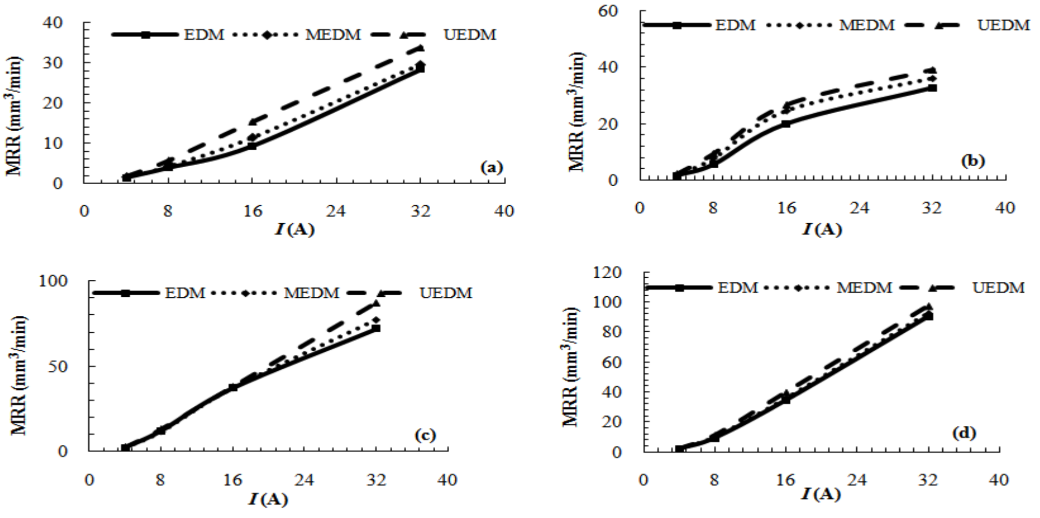

Figure 4 Effects of pulse current on material removal rate of EDM, MEDM and UEDM processes at (a) T_{on}=6.4µs (b) T_{on} =12.8µs (c) T_{on} =50µs (d) T_{on} =100µs

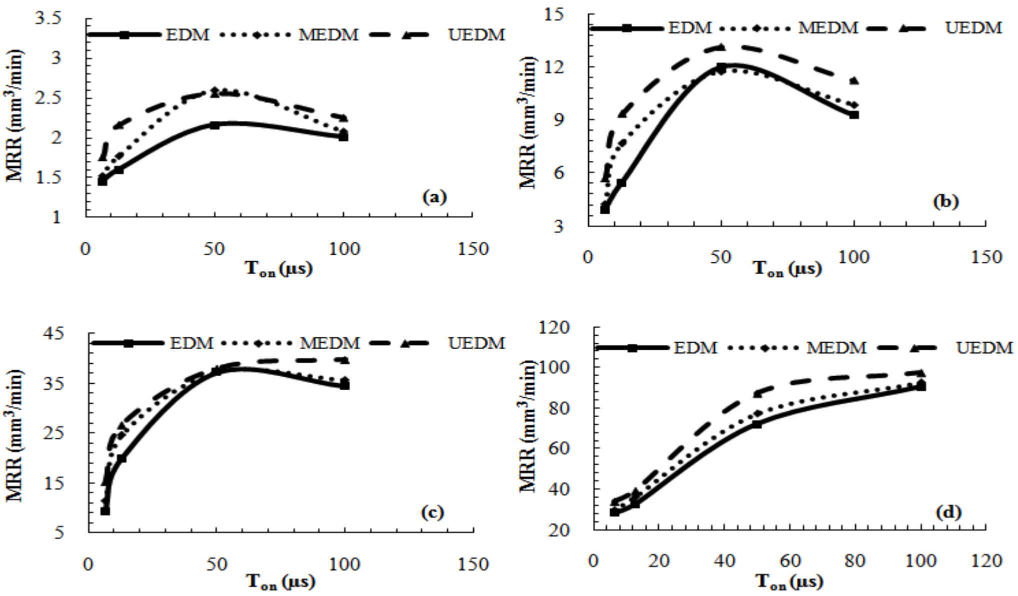

Figure 5 Effects of pulse on-time on the material removal rate of EDM, MEDM and UEDM processes at (a) I=4A (b) I=8A s (c) I=16A (d) I=32A

Figure (5) illustrates the influence of pulse on-time on the material removal rate of electrical discharge machining processes, electrical discharge machining with the magnetic field and electrical discharge machining along with ultrasonic vibrations of tool.
As shown in figure (5), with increasing pulse on-time up to 50 µs, the material removal rate of electrical discharge machining processes, electrical discharge machining along with the magnetic field and electrical discharge machining with the ultrasonic vibrations of the tool, increases at all of the currents, but after 50 µs, incremental rate of material removal rate is stopped or reduced.

By increasing the pulse on-time from 6.4 µs to 50 µs, at all of discharge currents, the amount of discharged energy to the gap distance is increased in accordance with equation 3 and therefore leads to a higher material removal rate. But after 50 µs to 100 µs, due to increasing gap pollution, caused by the presence of produced chips in gap distance, the number of arc pulses is increased and the material removal rate is reduced or its increasing trend is stopped.

As shown in figures (4) and (5), the material removal rate of the electrical discharge machining process along with the magnetic field at all levels of the discharge currents and the pulse on-times is greater than the electrical discharge machining process (with maximum increases of 41%). The usage of the magnetic field around gap distance in the electrical discharge machining process reduces the gap pollution and the number of arc pulses (according to the figure (6)) by attracting produced chips at the gap distance and improving the debris removal from the gap, so it increases the number of normal pulses and leads to more material removal rate. Also increase in ionization at plasma channel, as a result of the decrease in the mean free path of electrons movement inside plasma channel, with applying the external magnetic field around the gap distance in the electrical discharge machining process, decreases the spark delay time and increases the material removal rate. The restriction of plasma channel development due to the produced Lorentz force induced by applying the external magnetic field around the gap distance of EDM process, increases the material removal rate, too [14, 15].

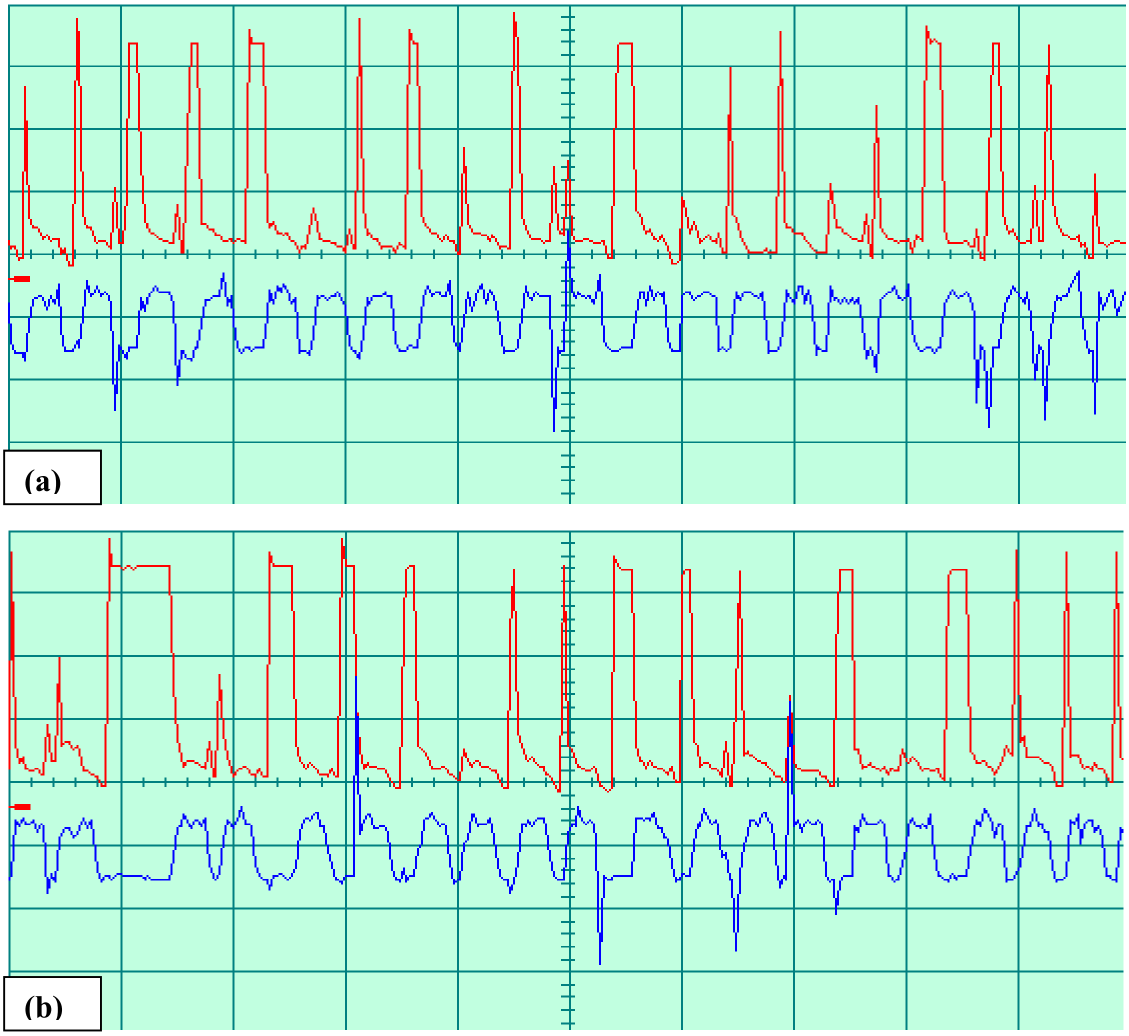

Figure 6 Voltage and current pulses at I= 16 A, T_{on}= 50 µs (a) EDM process (b) MEDM process

The force derived from the magnetic field due to the movement of charged particles within the plasma channel in the direction of decreasing plasma channel radius is obtained from equation 4. In this study, due to the placement of the N and S magnets poles in the special fixture and considering the right-hand rule, the generated force by the external magnetic field is also in the direction of decreasing the radius of the plasma channel and limiting its developement which is calculates by the equation 5.

$$F_m = e\,(\nu \times B_s) \tag{4}$$

$$F_{mo} = e\,(\nu \times B_E) \tag{5}$$

In equation 4 and 5, F_m is the force derived from the magnetic field due to the movement of charged particles within the plasma channel, F_{mo} is the force generated by the external magnetic field, e is the electron electrical charge, ν is the drift velocity of charged particles in the plasma channel, and derived from equation 6 [29], B_s is the magnetic field created around the plasma channel due to the movement of charged particles in the plasma channel, and calculated by the equation 7, and B_E is the external magnetic field created around the plasma channel.

$$\nu = \left(\frac{V}{V_m}\right) \times 10^4 \tag{6}$$

In equation 6, V is the discharge voltage in the electrical discharge machining process and V_m is the average discharge voltage.

$$B_s = \frac{\mu_0 \times I}{2\pi r} \tag{7}$$

In equation 7, μ_0 is the coefficient of magnetic permeability of vacuum and r is the radius of the plasma channel.

As shown in figures (4) and (5), the material removal rate of the electrical discharge machining process with ultrasonic vibrations of tool, at all discharge current levels and the pulse on-times, is greater than the electrical discharge machining process, (with maximum increase of 71%). By applying ultrasonic vibrations to the tool electrode in the EDM process, the debris removal from the gap distance is improved, therefore the amount of pollution in the gap distance and the number of abnormal pulses such as arcs decreases (according to the figure (7)), resulting in material removal rate increases. On the other hand, by occurrence of cavitation phenomenon at the end of the pulse's on-time, a larger amount of molten material is emitted from the molten puddle on the workpiece surface, and an increase occurs in material removal rate.

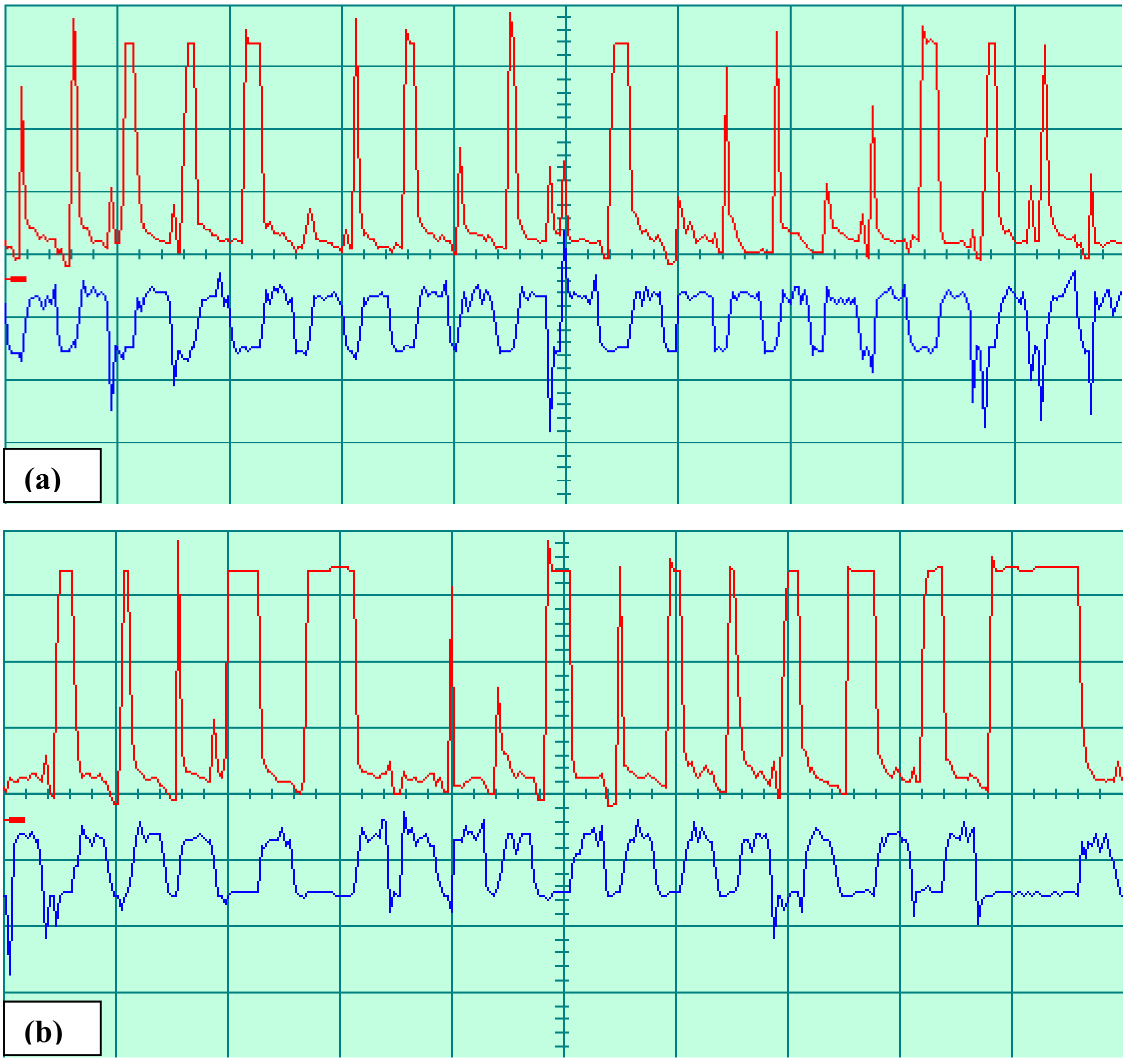

Figure 7 Voltage and current pulses at I= 16 A, T_{on}= 50 µs (a) EDM process (b) UEDM process

Also, according to figures (4) and (5), the material removal rate of the electrical discharge machining process with ultrasonic vibrations of tool, at all levels of the discharge currents, and all pulse on- times, is greater than electrical discharge machining process with the magnetic field. It is because of this fact that applying ultrasonic vibrations to tool is more effective than applying the external magnetic field around the gap distance of electrical discharge machining process in the case of reduction of gap pollution, decreasing number of arc pulses and increasing material removal rate. Figure (8) which compares the voltage and current pulses in these process, shows this fact that the number of arc pulses of electrical discharge machining process with ultrasonic vibrations of tool is lower.

An increase of 71% in material removal rate by applying ultrasonic vibrations to the tool, as well as an increase of 41% in material removal rate, by application of the external magnetic field around the gap distance is occurred at 8 A pulse current and 12.8 µs pulse on-time. It seems that the reason for this incident is to reduce the role and effect of applying ultrasonic vibrations to the tool and external magnetic field around the gap distance, with the increase in the chip produced and suspended at the gap distance, and gap pollution. When a large amount of chips is produced and suspended in the gap, the ability of the ultrasonic vibrations of the tool and the external magnetic field is reduced in the debris removal from gap distance.

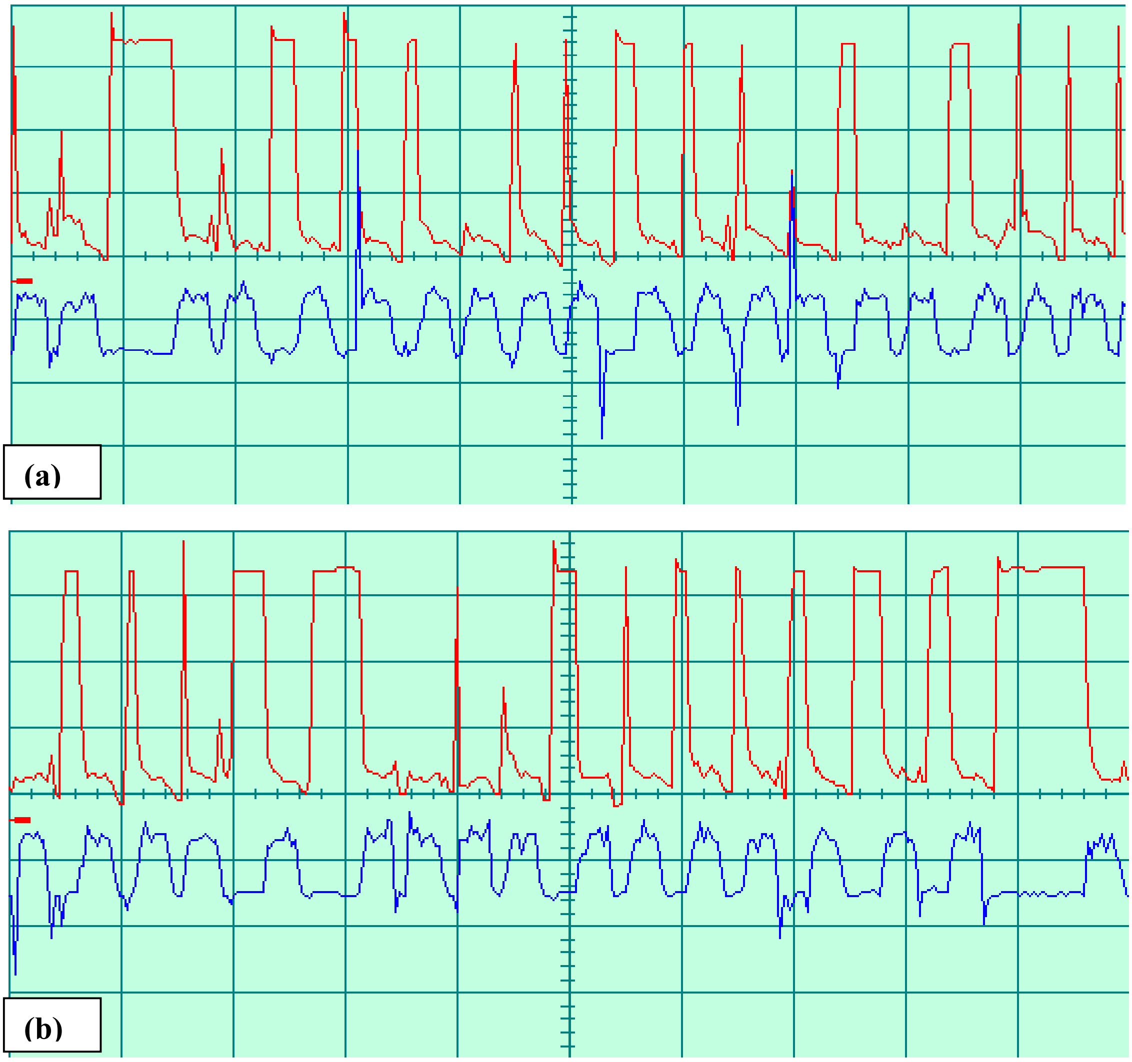

Figure 8 Voltage and current pulses at I= 16 A, T_{on}= 50 µs (a) MEDM process (b) UEDM process

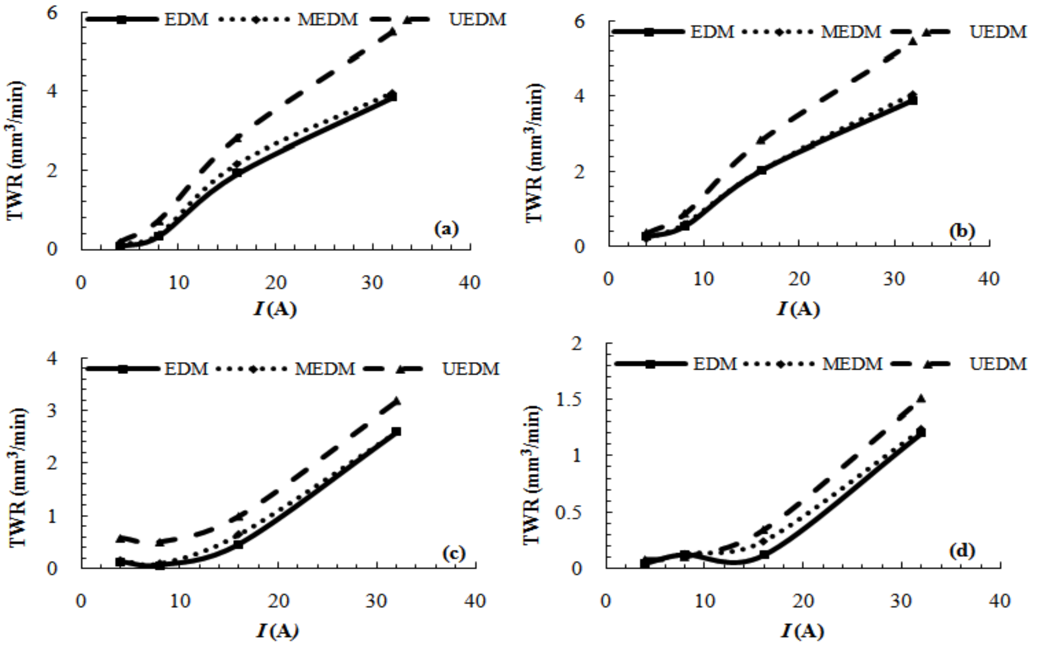

Figure 9 Effects of pulse current on tool wear rate of EDM, MEDM and UEDM processes at (a) T_{on} =6.4μs (b) T_{on} =12.8μs (c) T_{on} =50μs (d) T_{on} =100μs

3.2 Tool wear rate

Figure (9) illustrates the effects of the pulse current on the tool wear rate of the electrical discharge machining processes, the electrical discharge machining with magnetic field and the electrical discharge machining along with ultrasonic vibrations of tool.

As shown in figure (9), the tool wear rate of electrical discharge machining processes, the electrical discharge machining with magnetic field and the electrical discharge machining along with the ultrasonic vibrations of the tool, is increased at all pulse on-times, with increasing pulse current. By increasing pulse current from 4 A to 32 A in all pulse on-times, due to the increase in the amount of discharged energy to the gap distance, and increasing the heat produced on the surface of the tool electrode (according to equation 3), the amount of molten material from the tool and tool wear rate is increased. Figure (10) illustrates the effect of pulse on-time on the tool wear rate of the electrical discharge machining process, the electrical discharge machining with the magnetic field and the electrical discharge machining along with the ultrasonic vibrations of the tool. According to figure (10), with an increase in pulse on-time up to 12.8 μs, the tool wear rate for the electrical discharge machining process, electrical discharge machining with the magnetic field and the electrical discharge machining along with the ultrasonic vibrations of tool, increases at all pulse currents, but after 12.8 μs the tool wear rate is reduced.

By increasing the pulse on-time from 6.4 μs to 12.8 μs, at all pulse currents, the amount of discharged energy to the gap distance increases according to equation 3, resulting in a higher tool wear rate. Also, due to the positive polarity used in the experiments, considering the limited plasma channel up 12.8 μs, the more electrons motion and their collision with the tool (positive pole), increases the tool wear rate, but by increasing the pulse on-time from 12.8 μs to 100 μs, tool wear rate decreases due to the developed plasma channel and the increase in motions of positive ion and their collisions with the workpiece surface (negative pole) and the decrease in the collision of electrons with the surface of the tool.

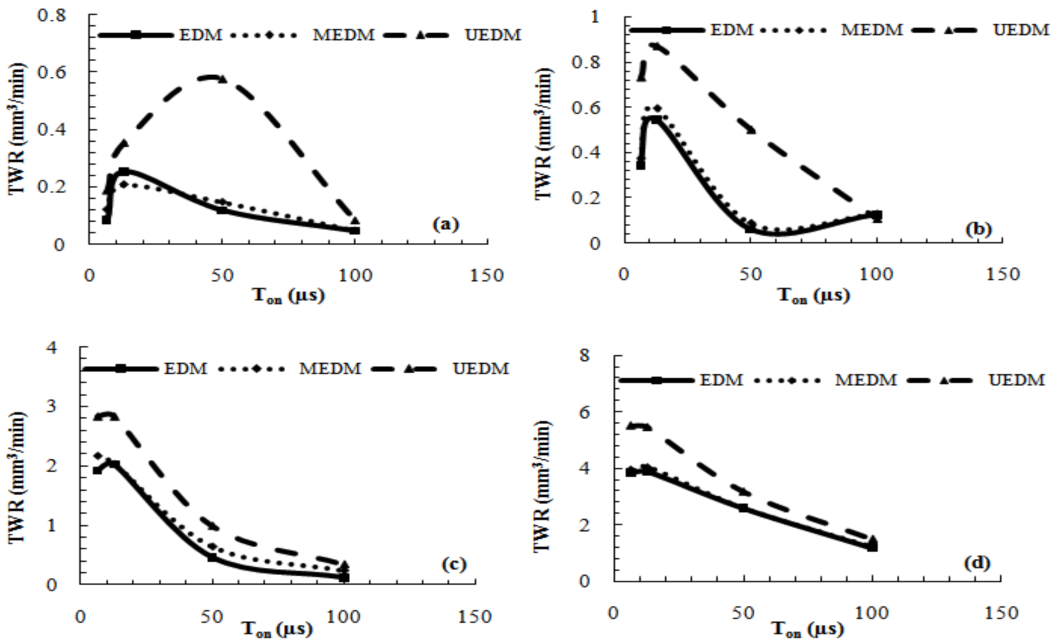

Figure 10 Effects of pulse on-time on tool wear rate of EDM, MEDM and UEDM processes at (a) I=4A (b) I=8A s (c) I=16A (d) I=32A

As shown in figures (9) and (10), the tool wear rate for the electrical discharge machining process along with the magnetic field, at all pulse current levels and pulse on-times, is slightly greater than electrical discharge machining process.

The application of the magnetic field around the gap distance in the electrical discharge machining process reduces the gap pollution and the number of arc pulses and increases the number of normal pulse and leads to more tools wear rate, by absorbing the produced chips at the gap distance and improving the debris removal from the gap distance.

The increase in ionization in plasma channel due to the decrease of the mean free path of electrons inside plasma channel by applying the external magnetic field around the gap distance in the electrical discharge machining process and also the limitation of the plasma channel due to the produced Lorentz force (which leads to higher current density) are the other factors for increasing the tool wear rate with the application of the external magnetic field around gap distance in the electrical discharge machining process.

In accordance with figures (9) and (10), the tool wear rate of the electrical discharge machining process along with the ultrasonic vibrations of tool, at all discharge current levels and pulse on-times, is greater than the electrical discharge machining process. By applying ultrasonic vibration to the tool electrode in the electric discharge machining process, the debris removal from the gap is improved; the amount of gap pollution and also the number of abnormal pulses such as the arc are decreased, so the tool wear rate is increased.

On the other hand, by occurrence the cavitation phenomenon at the end of pulse on-time, a larger amount of molten material from the molten puddle on the tool face is expulsed, therefore the tool wear rate increases.

Also, according to figures (9) and (10), the tool wear rate for the electrical discharge machining process with the ultrasonic vibrations of the tool, at all discharge current levels, and all pulse on-times, is greater than the electrical discharge machining process with the magnetic field.

3.3 Surface integrity

3.3.1 Surface roughness

Figure (11) illustrates the effects of pulse current on the surface roughness obtained from the electrical discharge machining processes, the electrical discharge machining with the magnetic field and the electrical discharge machining along with the ultrasonic vibrations of tool.
As shown in figure (11), the surface roughness obtained from electrical discharge machining processes, electrical discharge machining with magnetic field and electrical discharge machining along with the ultrasonic vibrations of tool, is increased at all pulse on-times, with increasing pulse current.

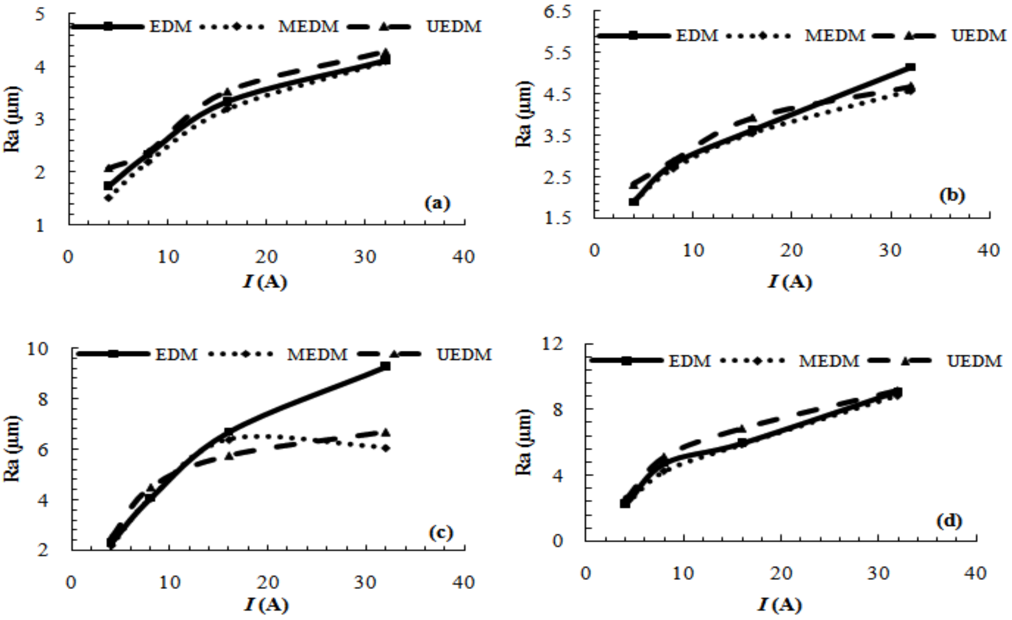

Figure 11 Effects of pulse current on surface roughness of EDM, MEDM and UEDM processes at (a) T_{on} =6.4µs (b) T_{on} =12.8µs (c) T_{on} =50µs (d) T_{on} =100µs

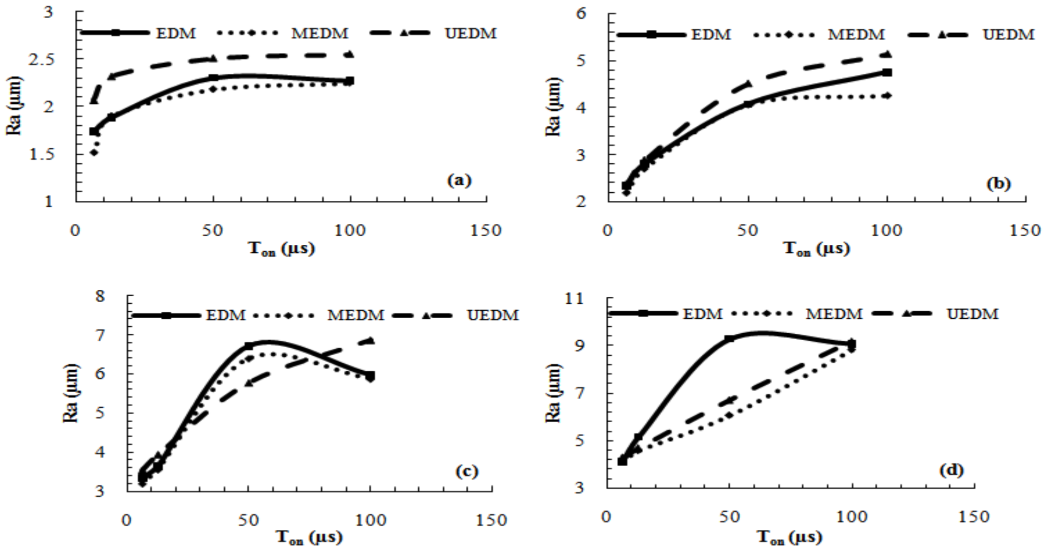

Figure 12 Effects of pulse on-time on the surface roughness of EDM, MEDM and UEDM processes at (a) I=4A (b) I=8A s (c) I=16A (d) I=32A

With increasing pulse current from 4 A to 32 A, due to increasing the amount of discharged energy to the gap distance and increasing the amount of heat generated on the workpiece surface (according to equation 3), the dimensions of the generated craters on the workpiece surface are increased and more surface roughness is achieved. This phenomenon was observed at all pulse on-times. Figure (12) illustrates the influence of pulse on-time on surface roughness obtained from electrical discharge machining processes, electrical discharge machining with magnetic field and electrical discharge machining with ultrasonic vibrations of tool.

As shown in figure (12), with increasing pulse on-time up to 50 μs, the surface roughness obtained from electrical discharge machining processes, electrical discharge machining with the magnetic field and electrical discharge machining along with the ultrasonic vibrations of tool, increases at all pulse currents, but after 50 μs, the obtained incremental surface roughness trend is stopped or reduced. By increasing the pulse on-time from 6.4 μs to 50 μs, at all the pulse currents, the amount of discharged energy to the gap distance according to equation 3 increases and the dimensions of the generated craters on the workpiece surface increase and more surface roughness is achieved. But after 50 μs up to 100 μs, due to the increasing gap pollution induced by produced chips, the number of arc pulses is increased. The occurrence of the arc pulses can decrease the surface roughness, and so the machined surface roughness increasing trend is stopped after 50 μs and in some cases, it becomes a decreasing trend.

According to figures (11) and (12), the surface roughness obtained from the electrical discharge machining process along with the magnetic field, at all levels of the pulse currents and pulse on-times is less than the electrical discharge machining process. The maximum reduction in surface roughness by applying external magnetic field is 35%. By applying the magnetic field around the gap distance in the electrical discharge machining process, the elimination of the produced chips and debris removal from the gap distance are improved and the probability of re-attaching the chips to the surface of the machined workpiece, the number of abnormal pulses like short circuits and surface roughness is reduced. Also, the horizontal motions of the sharp small chips on the machined surface by applying the magnetic field around the gap distance is one of the main factors of reducing the roughness in machined surface [30]. A 35% decrease of the surface roughness by applying an external magnetic field around the gap distance has been achieved in 32 A pulses current and 50 μs pulse on-time. In spite of the decreasing the ability of the external magnetic field to eliminate chips outside of the gap, by increasing the amount of produced chips (at 32 A and 50 μs), the large amount of produced sharp chips and their much horizontal movements at the machined surface leads to the greater wear on non-uniformity of surface and reduction of the machined surface roughness in this machining condition.

As shown in figures (11) and (12), the obtained surface roughness from the electrical discharge machining process along with the ultrasonic vibrations of tool, in all cases is more than the electrical discharge machining process. By applying ultrasonic vibrations to tool in the electrical discharge machining process, and improving the repulsion of generated chips from machining area, the number of abnormal pulses is decreased and as a result, the number of normal pulses and the dimensions of the craters formed on the machining surface are increased and the roughness of the machining surface increases. On the other hand, the occurred cavitation phenomenon at the end of the pulse on-time in the electrical discharge machining process with the ultrasonic vibrations of tool causes the large volumes of molten material repulses from molten puddle, so the dimensions of the craters produced at the machined surface, and also the machined surface roughness are increased.

Also, according to figures (11) and (12), the obtained surface roughness from the electrical discharge machining process along with the magnetic field, at all discharge current levels, and all pulse on-times, is less than the electrical discharge machining process with the ultrasonic vibrations of tool.

3.3.2 Surface quality

Figure (13), demonstrates the machined surfaces of the electrical discharge machining process, the electrical discharge machining with the magnetic field and the electrical discharge machining along with the ultrasonic vibrations of tool. According to figure (13), the quality of the machined surfaces is improved by applying ultrasonic vibrations to tool and magnetic field around gap distance of electrical discharge machining process, and this improvement is higher in the case of applying ultrasonic vibration to tool electrode. By applying ultrasonic vibrations to the tool, the cavitation phenomenon has occurred and it creates a high-velocity fluid jet and improves the elimination of chips from the machining gap. So the thickness of the recast layer formed on the machined surface, which contains various defects, is decreased. The application of a magnetic field around the gap distance also helps to absorb the existing chips in gap distance and prevent the accumulation of chips and other pollutions in the machining area, thereby prevent arc pulses and surface damages. Therefore by applying ultrasonic vibrations to tool and also by applying the magnetic field around the gap distance, better surface quality with regular structures and fewer defects (less cracks, cavities, beads of debris and residual spherical materials) is generated. It is worth to mention that, the improvement in surface quality is more in the case of applying ultrasonic vibrations to the tool in comparison with applying magnetic field around the gap distance of EDM process.

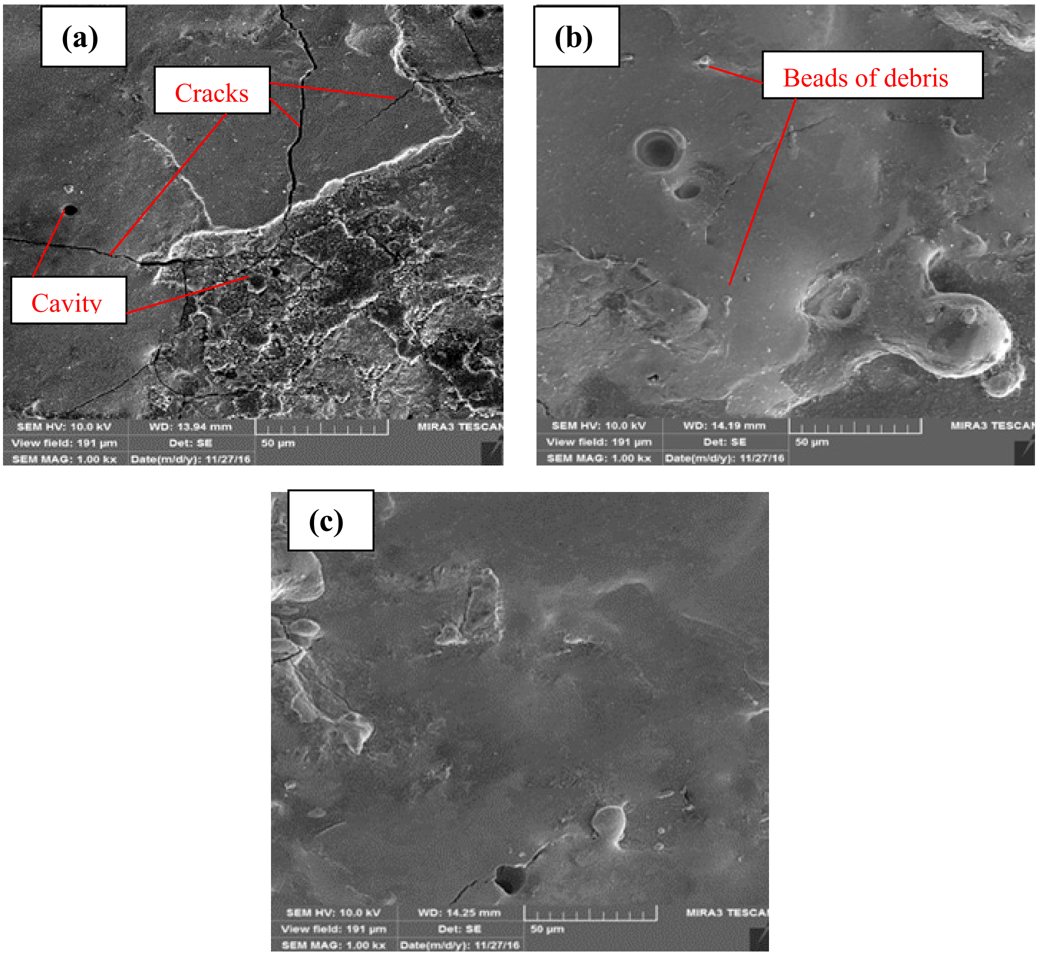

Figure 13 The SEM picture of machined surfaces in I=32 A, T_{on}=50 µs with (a) EDM (b) MEDM and (c) UEDM processes

4 Conclusion

In this study the material removal rate, tool wear rate and machined surface integrity of electrical discharge machining processes, electrical discharge machining with magnetic field and electrical discharge machining with ultrasonic vibrations of tool, were studied and compared with together. The main obtained results of this study can be summarized as follow:

- The material removal rate, tool wear rate and the machined surface roughness are increased by applying the ultrasonic vibrations to tool electrode in the electrical discharge machining process. The highest increase in material removal rate, in this case, was 71%.
- The application of the magnetic field around the gap distance in the electrical discharge machining process increases the material removal rate and the tool wear rate and reduces the machined surface roughness. The highest increase in material removal rate, in this case, was 41% and the maximum amount of surface roughness reduction was 35%.
- The increase in material removal rate and tool wear rate by applying ultrasonic vibrations to the tool is greater as compared with applying the external magnetic field around the gap distance.
- The machined surfaces integrity is improved and better surface with fewer defects is obtained by applying ultrasonic vibrations to tool and external magnetic field around gap distance in the electrical discharge machining process.
- The improvement in surface integrity has a greater level in the case of applying ultrasonic vibration to the tool electrode.

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Nomenclature

I	pulse current
T_{on}	pulse on-time
T_{off}	pulse off-time
V	discharge voltage
MRR	material removal rate
M_{W1}	the weight of the workpiece before machining
M_{W2}	the weight of the workpiece after machining
t	the machining time
ρ_W	the workpiece density
TWR	the tool wear rate
M_{T1}	the tool weight before machining
M_{T2}	the tool weight after machining
ρ_T	the tool density
Q	the generated heat
R	the electrical resistance between the tool and the workpiece
V_m	the average discharge voltage
μ_0	the coefficient of magnetic permeability of vacuum
r	the radius of the plasma channel
F_m	the force derived from the magnetic field due to the movement of charged particles
F_{mo}	the force generated by the external magnetic field
e	the electron electrical charge
ν	the drift velocity of charged particles in the plasma channel
B_s	magnetic field created on the plasma channel due to movement of charged particles
B_E	the external magnetic field created around the plasma channel