Effects of Al_2O_3 powder on electro discharge machining process of nickel-titanium shape memory alloy

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Shape memory alloys are kind of alloys with different properties like high fatigue strength, oxidation, creep, vibration and high functional temperature. These alloys are widely applied in aerospace, automobile, medicine and dentistry industries. Electro Discharge Machining is an innovative method in machining of shape memory alloys. Surface roughness and low material removal rate are considered as main problems in this technique. In the present study, the effect of Al_2O_3 powder on Electro Discharge Machining parameters including surface roughness, tool wear rate, removal rate and surface integrity was studied. The results show that utilizing Al_2O_3 in machining of NiTi shape memory and increase in material removal rate rises tool erosion and surface roughness. On the other hand, increase in pulse-on time and voltage causes decrease in tool erosion and obtaining better material removal rate. Surface integrity results indicate that using Al_2O_3 powder creates shallower holes on the workpiece and reduces surface defects and cracks.

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1. Introduction

Shape memory alloys (SMAs) are a type of metals that remembers their original shapes. SMAs are useful for such things as actuators which are materials that change shape, stiffness, position, natural frequency, and other mechanical characteristics in response to temperature or electromagnetic fields [1]. SMAs display two distinct crystal structures or phases. Temperature and internal stresses determine the phase that the SMA will be at. Martensite exists at lower temperatures, and austenite exists at higher temperatures. When a SMA is in martensite form at lower temperatures, the metal can easily be deformed into any shape. When the alloy is heated, it goes through transformation from martensite to austenite. In the austenite phase, the memory metal remembers the shape it had before deformation. SMAs are known for their excellent memory phenomena accompanied with practical applicability. The special functional properties of SMAs are Shape Memory Effect (SME) and Superelastic Effect (SE). SMAs may have two different kinds of Shape Memory Effect; these are common known as one-way shape memory effect (OWSME) and two-way shape memory effect (TWSME). The Shape Memory Effect changes with temperature variation are mainly attributed to martensitic phase transformation [2]. The potential uses for SMAs especially as actuators have broadened the spectrum of many scientific fields. Nickel-titanium alloys have been found to be the most useful of all SMAs. Other shape memory alloys include copper-aluminum-nickel, copper-zinc-aluminum, and iron- manganese-silicon alloys [3]. The generic name for the family of nickel-titanium alloys is Nitinol. Nitinol is being used in a variety of applications. They have been used for military, medical, safety, and robotics applications. As Nitinol has a wide range of applications it will be more demanding in near future so different techniques will be needed to form and machine the Nitinol. Due to the toughness and strength of the Nitinol alloys electro discharge machining (EDM) can be recommended as a machining method. The EDM process is used widely in machining hard metals and alloys in aerospace and die industries [4, 5]. Its main applications are in pressure casting dies, forging dies, powder metallurgy, and injection mold. This method is commonly used for profile truing of metal bond diamond wheel, micro nozzle fabrication, drilling of composites, and manufacturing of moulds and dies in hardened steels [6, 7]. EDM is a reproductive shaping process in which the form of the tool electrode is replicated in the workpiece. This process involves material erosion of electrically conductive materials by electrical discharges [8]. In EDM, the removal of material is based upon the electro discharge erosion (EDE) effect of electric sparks occurring between two electrodes that are separated by a dielectric liquid as shown in Fig. 1.

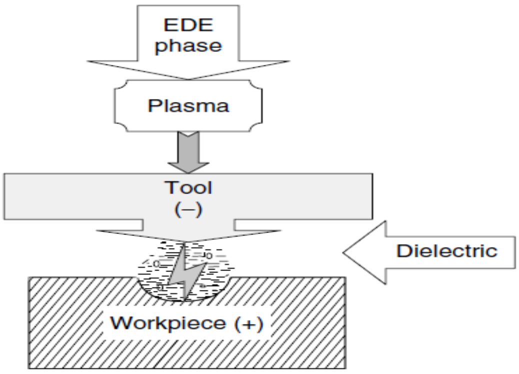

Fig. 1. Electro discharge machining [9].

Material removal takes place as a result of the generation of extremely high temperatures due to the high-intensity discharges that melt and evaporate the two electrodes. A series of voltage pulses of magnitude about 20 to 120 V and frequency on the order of 5kHz is applied between the electrodes, which are separated by a small gap, typically 0.01 to 0.5mm. The basic parameters of conventional EDM are the pulsed current, pulse-on duration, and pulse-off duration. Metals with a high melting point and good electrical conductivity are usually chosen as tool materials for EDM. Graphite is the most common electrode material since it has fair wear characteristics and is easily machinable and small flush holes can be drilled into graphite electrodes. Copper has good EDM wear and better conductivity. Nowadays, EDM is used to machine the most of the new materials which have high ability and applicability. Electrically conductive ceramics and ceramic composites are EDMed by either melt formation for low melting materials or thermal spalling for refractory materials [10]. Ceramic composites such as Al_2O_3/TiC/Mo/Ni have been machined by EDM. In addition, EDM has also been used for machining Al_2O_3 particle reinforced 6061 aluminum matrix composites (Al_2O_3p/6061 Al) [11], metal matrix composites such as AlSi7 Mg/SiC and AlSi7 Mg/Al2O3 [12], TiN/Si3N4 composites, SiC [13], Al-SiC composite [14], Al_2O_3 [15], and different conductive ceramics such as cobalt-bonded tungsten carbide (WC - Co), hot-pressed boron carbide (B4C) and reaction-bonded silicon carbide [16]. These days it is so important how to increase material removal rate with high precision and lower workpiece surface hardness. Great efforts have been done to achieve this aim such as planetary movement of electrode, vertical oscillatory motion of electrode with specific frequency, change of polarities, multiple insulated electrodes with individual pulse period, and coating of electrode with high electrical resistance. But acceptable efficiency has not been obtained by these techniques. One of the recent methods is to add liquid or powder materials to dielectric. According to the reports and articles, adding powder is effective to improve surface hardness, increase in material removal rate and stability of machining [17, 18]. The effect of graphite powder added into dielectric was investigated by Geswami in 1981 and showed that adding graphite powder causes break down voltage reduction and gap distance increase. Furthermore, stability of machining process improves due to increase in material removal rate [19]. Then, several researchers began to do determined experiments on the high hardness materials even brittle ceramics by using different types of very fine powder. Mori studied the effects of adding powder into dielectric [20]. Yan and Chcn investigated the effects of aluminum powder added into dielectric on TI6AI-4V, SD11 in working machine [21, 22]. In 2002, Ghoreyshi did series of experiments by using a metal powder such as copper, a metal oxide powder like aluminum oxide with purity of 78%, and a semi-conductive powder as silicon carbide in the dielectric of EDM and investigated the effects of these powders on the machining parameters and compared them. In this research, the influence of input parameters including pulse current, voltage gap, pulse-on time, and pulse-off time on the output parameters like surface roughness and material removal rate was studied by adding Al_2O_3 powder into deionized water for machining nickel-titanium alloy.

2. Primary materials and equipments

NiTi60 with a dimension of 50*80 mm and thickness of 20mm was used in the tests and it was cut and ground by wire-cut machine. Physical and mechanical properties of this alloy are given in Table 1. In the machining tests, a copper electrode with a diameter of 10mm and a length of 40mm was used as the tool. The density of this copper electrode is 8.93 gr/cm^3. The machining tests were done with the machine model M204H manufactured by Tehran-Ekram Co. Weight difference of tool electrode and work piece was measured by AND GR-300 balance with sensitivity to 0.1 milligrams and surface roughness by Mahr M300-RD18 roughness measurement device before and after machining. An electronic microscope model Philips XL 30 was utilized for surface topography. Dielectric fluid used in all tests was deionized water with Al_2O_3 powder. All tests were performed in Iso-pulse condition. A pump was applied as stirrer to prevent deposition of Al_2O_3 powder during the process. Thermo dynamical and physical properties of Al_2O_3 powder are shown in Table 2.

Table 1. Physical and mechanical properties of NiTi60 [23].

Density	6.45 G/cc
Tensile strength, ultimate	754 - 960 Mpa
Tensile strength, yield	560 Mpa
Modulus of elasticity	75.0 Gpa
Electrical resistivity	0.0000820 Ohm-cm
Magnetic susceptibility	0.00000380
Specific heat capacity	0.320 J/g-°c
Thermal conductivity	10.0 W/m-k
Melting point	1240 -1310 °C
Nickel, Ni	55.0 %
Titanium, Ti	45.0 %

Table 2. Physical and mechanical properties of Al_2O_3 powder.

Density	0.9 g/cm^3
Electrical resistance	10^{14} Ohm.cm
Thermal conductivity	29 W/m-K
Melting point	2000 °c
Compressive strength	2500 Mpa

3. Test design

Providing all test conditions is so difficult to design the tests so it's necessary to utilize a technique to perform proper and accurate tests. Taguchi method was applied in the present study. Current pulse, open voltage circuit, pulse on time and pulse off time have large influence on material removal rate, tool erosion and surface roughness [24]. The main object of these tests is to study the effects of Al_2O_3 powder on the output parameters of EDM including material removal rate, tool erosion, and surface roughness. Table 3 indicates input parameters of the process and test levels. Minitab@16.1.1 was used to do analysis. Conditions and setting of EDM are shown in Table 4.

Table 3. Input parameters of machining process.

Input parameters	Level 1	Level 2	Level 3
Pulse current (A)	10	15	20
Open circuit voltage (V)	80	250	-
Pulse-on time (µs)	35	50	100
Pulse-off time (µs)	30	70	200

Table 4. Conditions and setting of machine.

Parameters	Specifications
Workpiece (-)	NiTi60
Electrode (+)	Copper
Electrode diameter	10mm
Time of machining	6min
dielectric	Deionized water
Type of powder	AL_2O_3
Size of powder	50µm
Mixture amount	3gr/Lit

Material removal rate and tool erosion are two parameters to evaluate the efficiency of electro discharge machining process which given in equation 1 and 2 [25].

$$MRR = \frac{\Delta m/\rho_{NiTi}}{t_M} \times 1000 \quad (1)$$

$$TWR = \frac{\Delta m/\rho_{Copper}}{t_M} \times 1000 \quad (2)$$

Where,
Δm; is the mass differential of work piece or tool electrode before and after machining (gr), ρ_{NiTi}; is density of work piece (gr/cm^3), ρ_{copper}; is density of tool electrode (gr/cm^3), t_M; is time of each test (min), MRR; is material removal rate (mm^3/min), TWR; is tool wear rate (mm^3/min).

Table 5 indicates output values of the process and test design. SR indicates surface roughness and Delta T and Delta W are weight difference of tool and work piece before and after machining, respectively.

Table 5. Test design and output values.

Experiment number	Voltage	Current	Pulse on Time	Pulse off Time	Delta W	MRR	Delta T	TWR	SR
1	1	1	1	1	0.125	3.186	0.024	0.449	2.800
2	1	1	2	2	0.135	3.488	0.026	0.486	2.850
3	1	1	3	3	0.145	3.746	0.028	0.524	2.910
4	1	2	1	1	0.175	4.521	0.020	0.374	3.080
5	1	2	2	2	0.178	4.599	0.021	0.393	3.100
6	1	2	3	3	0.180	4.651	0.023	0.430	3.150
7	1	3	1	2	0.117	3.023	0.006	0.112	3.480
8	1	3	2	3	0.128	3.307	0.008	0.149	3.485
9	1	3	3	1	0.139	3.591	0.009	0.168	3.490
10	2	1	1	3	0.240	6.201	0.023	0.430	3.495
11	2	1	2	1	0.350	9.043	0.027	0.505	3.500
12	2	1	3	2	0.340	8.785	0.029	0.543	3.510
13	2	2	1	2	0.260	6.718	0.021	0.393	3.530
14	2	2	2	3	0.310	8.010	0.023	0.430	3.560
15	2	2	3	1	0.380	9.819	0.025	0.468	3.580
16	2	3	1	3	0.280	7.235	0.018	0.337	3.600
17	2	3	2	1	0.360	9.302	0.019	0.355	3.610
18	2	3	3	2	0.380	9.819	0.017	0.318	3.620

4. Material removal rate

Fig. 2 illustrates the effect of input parameters such as current, voltage pulse-on time, pulse-off time and Al_2O_3 powder on material removal rate. When Al_2O_3 powder is used ions and electrons move toward the electrodes (work piece and tool) and collide with the suspended particles of Al_2O_3 powder. These particles absorb energy and generate a great number of ions and electrons and increase ignitions which results in material removal rate increase [26]. The collision of powder particles with work piece surface due to electro discharge effect is another factor to increase material removal rate [27]. Resistivity of the gap is reduced because of low thermal conductivity of Al_2O_3 powder and increase in dielectric temperature so in order to adjust the gap resistivity the machine rises the gap between tool and work piece. Material removal rate increases as a result of increasing the gap distance and the number of accurate sparks and better washing. As shown in Fig. 2, increase in current, voltage and pulse-on time causes increasing material removal rate.

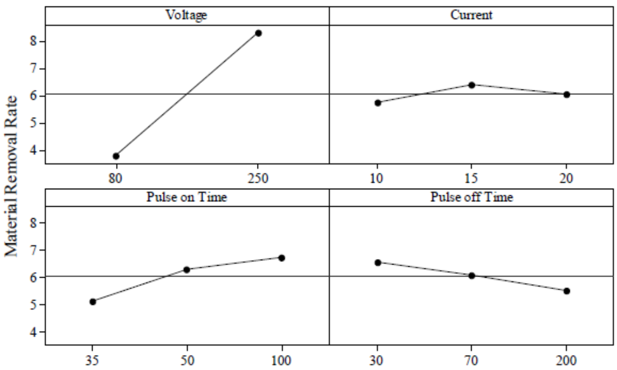

Fig. 2. Effect of input parameters of EDM and Al_2O_3 powder on material removal rate.

5. Tool wear rate

Tool wear rate via current, pulse-on time, pulse-off time, and voltage at 3gr/Lit mixture amount of Al_2O_3 powder is indicated in Fig. 3. Tool electrode should have high electrical conductivity and low tool wear rate [28]. The copper tool wear rate can be obtained by measuring the mass difference of tool electrode before and after machining and using equation 2. Gap distance between tool electrode and work piece is increased by adding Al_2O_3 powder to dielectric powder and as a result of reduction in break down resistance (strength) of dielectric fluid. So Plasma channel gets larger and thermal energy of electro discharge process distributes in more extensive space which leads to reduction in electrical power, material removal from electrode surface and eventually tool wear rate. According to Fig. 3, as voltage and pulse-on time increase tool wear rate decreases.

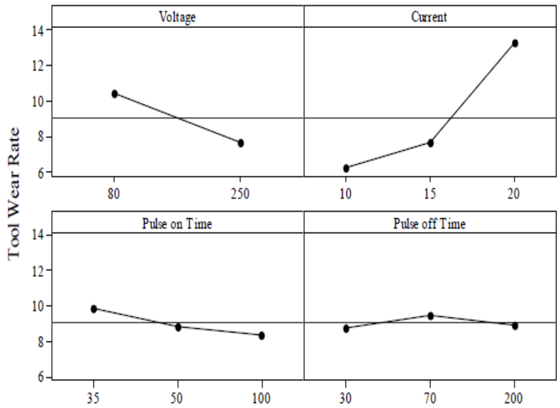

Fig. 3. Effect of input parameters of EDM and Al_2O_3 p owder on tool wear rate.

6. Surface roughness

Adding powder particles into the plasma channel break down resistance of dielectric reduced and spark control serve system increases gap distance between two electrodes in order to create more stable electro discharge conditions compared with the conventional electro discharge machining. Longer and wider electro discharge channel causes decrease in electrical power density therefore shallower holes produced at the machining surface and surface roughness is reduced. As the thermal conductivity of powder particles increases more thermal energy is dispersed out of the machining gap distance. Adding Al_2O_3 powder to the dielectric leads to increase in ignition frequency and decrease of electrical energy density. So ignitions uniformly distributed among powder particles which results in uniform distribution of electro discharges, uniform material removal from work piece surface and improving the surface quality [15]. The effect of voltage, current, pulse-on time and pulse-off on surface roughness is demonstrated in figure 4. Using the powder during the machining withdraws the heat quickly from the work piece and reduces the thermal stresses. Less thermal stress creates fewer cracks at the surface and improves surface quality. Adding powder to the dielectric should not exceed the optimal limit and if exceeds this limit surface roughness will increase. If powder concentration in fluid exceeds the limit, the amount of suspended particles in gap distance of work piece and tool electrodes will increase. Subsequently, the probability of instability increases in electro discharge process in the forms of short circuit and arcing. Therefore, non-uniformity of ignitions increases and surface becomes rougher. Instability in electro discharge process makes the distribution of electrical power at the machining surface less uniform and impact forces of electro discharges at the surface become more inhomogeneous. As observed in Fig. 4, with 3gr/Lit Al_2O_3 powder and by increasing current, voltage and pulse-on time ignition energy and eventually surface roughness will increase.

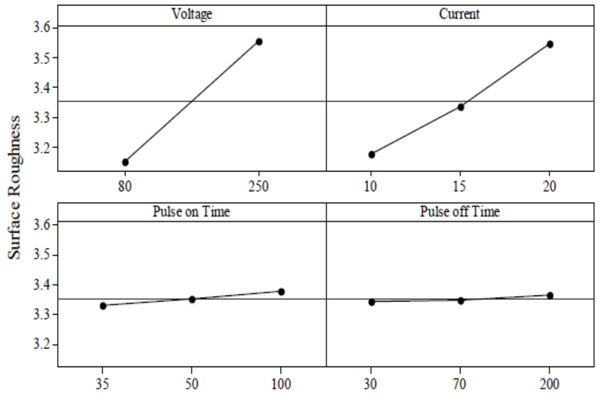

Fig. 4. Effect of input parameters of EDM and Al_2O_3 powder on surface roughness.

7. Surface integrity

Surface quality is evaluated by parameters like surface roughness, surface hardness, surface cracks, residual stresses and white layer of pits and holes [29]. The effect of Al_2O_3 powder on the integrity of the surface sparked at 1000X magnification and with the same machining conditions was compared in Figs. 5 and 6. For these samples voltage, current, pulse-on time and pulse-off time are 80V, 15A, 50µs, and 70µs, respectively. Due to fast melting of work piece by electro discharge and then its fast freezing by means of dielectric fluid several defects such as surface and sub-surface defects, pits and holes, residual stresses, superficial holes and heat affected areas are created at the surface of work piece [30]. These surface defects results in less hardness of work piece and make it erosion and corrosion resistant. According to Fig, 5, the surface machined by means of Al_2O_3 powder is smoother and more uniform, in addition, its pits and holes and the density of the cracks are reduced. Surface integrity reveals that particles of Al_2O_3 powder produce a surface with higher quality compared with the case in which there is no powder. Concentration of Al_2O_3 powder in dielectric fluid influences on surface roughness. Increasing the concentration above 3gr/Lit rises roughness of surface and cracks. There is an optimal concentration in dielectric fluid for each type of powder which results in optimal surface quality. Exceeding this optimal amount increases the concentration of suspended particles in the gap distance between work piece and tool electrodes as well as the possibility of short circuit and arcing and makes the machined surface less uniform. In addition, having a concentration above this optimal amount causes more instability in electro discharge process and creates a non uniform distribution of electrical power on the machined surface, in addition, makes the surface of work piece more inhomogeneous.

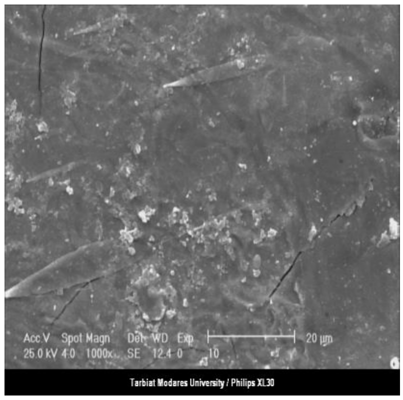

Fig. 5. Surface machined by means of Al_2O_3 powder.

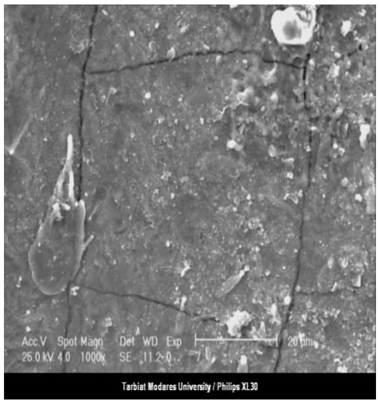

Fig. 6. Surface machined without of Al_2O_3 powder.

8. Conclusion

In this study, the effects of machining parameters including voltage, current, pulse-on time, and pulse-off time and using Al_2O_3 powder on the ability of machining NiTi were investigated. The concentration of Al_2O_3 powder in dielectric fluid was 3gr/Lit. Adding Al_2O_3 powder to deionized water increases the gap distance between work piece and tool and improves material removal rate and surface roughness. In electro discharge machining by means of powder, physical and thermo dynamical properties of powder such as density, electrical resistivity and thermal conductivity play an important role in output parameters like material removal rate, tool wear and surface roughness. As the concentration of particles of Al_2O_3 powder in dielectric exceeds a limit the amount of suspended particles increases in the gap distance as well as the probability of instability in electro discharge process. In this process, rising the voltage, current and pulse-on time leads to increase in material removal rate. Furthermore, increasing the voltage, current and pulse-on time and using Al_2O_3 powder leads to increase in surface roughness. Tool wear decreases as voltage and pulse-on time increase. Comparing the integrity of machined surface in the cases of with powder and without powder the greatest amount of cracks, pits and holes and roughness at the surface obtained when any powder was used. Fewer pits and holes and smoother machined surface achieved by adding Al_2O_3 powder. Adding different amount of Al_2O_3 powder to the deionized water varies material removal rate, surface roughness and tool wear. The best surface roughness and material removal rate obtained at 3gr/Lit.

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