Investigation of the Parameters of EDM Process Performed on Smart NiTi Alloy Using Graphite Tools

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Abstract: Shape Memory Alloys (SMAs) are types of Smart Materials (SMs) which are used in many industries nowadays. The high hardness value and the intelligence of these alloys have made the traditional machining processes not cost effective or incapable of machining ability these metals. The NiTi alloy is one of the SMAs, which are used in aerospace and medical industries. Electrical Discharge Machining (EDM) is a known method for the machining of shape memory alloys. In this research, the effect of input parameters of electrical discharge machining including the voltage (V), discharge current (A), pulse-ON-duration (µs), pulse-OFF-duration (µs), tool material and the dielectric on the material removal rate (MRR), tool wear rate and surface roughness has been investigated for NiTi alloy. Graphite tools and de-ionized water have been used for the machining operation, and the Taguchi's method, LI8 orthogonal array and the 'Minitab R.16.1.1' software have been employed for the design of experiment. The results indicate that with the increase of discharge current, the tool wear, material removal rate and surface roughness increase. The increase of voltage causes the reduction of tool wear and material removal rate, but it has little effect on surface roughness. With the increase of pulse-ON-duration, the surface roughness increases and the material removal rate diminishes. Also the increase of pulse-OFF-duration, up to a certain time, leads to the increase of material removal rate and tool wear rate (TWR) and the reduction of surface roughness.

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Keywords: Electrical discharge machining; Shape memory alloys; Smart material; Graphite tool; Material removal rate; Tool wear rate

1. Introduction

Smart materials are types of materials that can detect external stimuli and environmental changes. These alloys enjoy properties such as high corrosion resistance, high electrical resistivity, good mechanical properties, fatigue resistivity and compatibility with body tissue, which make them suitable to be used in aerospace and medical industries [1, 2]. Nickel–titanium (NiTi) alloys are commonly used in shape memory applications, although many other kinds of alloys also exhibit shape memory effects. These alloys can exist in final product form in two different temperature-dependent crystalline states or phases. The primary and higher temperature phase is called the austenite state. The lower temperature phase is called the martensite state. The physical properties of the material in the austenite and martensite phases are quite different. The material in the austenite state is strong and hard, while it is soft and ductile in the martensite phase. The austenite crystal structure is a simple body-centered cubic structure, while martensite has a more complex rhombic structure. With respect to its stress–strain curve, the higher temperature austenite behaves similarly to most metals. The stress– strain curve of the lower temperature martensitic structure, however, almost looks like that of an elastomer in that it has plateau stress-deformation characteristics where large deformations can easily occur with little force. In this state, it behaves like pure tin, which can (within limits) be bent back and forth repeatedly without strain hardening that can lead to failure. The thermally induced shape memory effect is associated with these different phases. In the primary high temperature environment, the material is in the austenite phase. Upon cooling, the material becomes martensitic. No obvious shape change occurs upon cooling, but now the material can be mechanically deformed. It will remain deformed while it is cool. Upon heating, the austenitic structure again appears and the material returns to its initial shape. A related mechanically induced phenomenon called superelasticity can also take place. The application of a stress to a shape memory alloy being deformed induces a phase transformation from the austenite phase to the martensite phase (which is highly deformable). The stress causes martensite to form at temperatures higher than previously and there is high ductility associated with the martensite. The associated strains or deformations are reversible when the applied stress level is removed and the material reverts to austenite. High deformations, on the order of 5–8%, can be achieved. Changes in the external temperature environment are not necessary for the superelasticity phenomenon to occur [3].

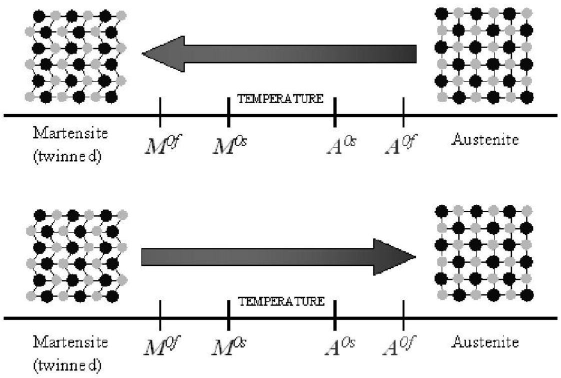

Figure 1. Phase transformation resulting from temperature in shape memory alloys without the application of force [4]

Considering the importance of temperature change in these types of alloys and their high strength and hardness, the use of traditional techniques for the machining of these alloys is not cost effective [5]. One of the methods which are appropriate for the machining of these alloys and which do not depend on the hardness and strength of the workpiece is electrical discharge machining (EDM) [6,7]. EDM is the process of machining electrically conductive materials by using precisely controlled sparks that occur between an electrode and a workpiece in the presence of a dielectric fluid. The electrode may be considered the cutting tool. EDM differs from most chip-making machining operations in that the electrode does not make physical contact with the workpiece for material removal. Since the electrode does not contact the workpiece, EDM has no tool force. The electrode must always be spaced away from the workpiece by the distance required for sparking, known as the sparking gap. Should the electrode contact the workpiece, sparking will cease and no material will be removed. Sparking occurs in a frequency range from 2,000 to 500,000 sparks per second causing it to appear that many sparks are occurring simultaneously. The spark removes material from both the electrode and workpiece, which increases the distance between the electrode and the workpiece at that point. EDM is a thermal process; material is removed by heat. Heat is introduced by the flow of electricity between the electrode and workpiece in the form of a spark. Material at the closest points between the electrode and workpiece, where the spark originates and terminates, are heated to the point where the material vaporizes. While the electrode and workpiece should never feel more than warm to the touch during EDM, the area where each spark occurs is very hot. The area heated by each spark is very small so the dielectric fluid quickly cools the vaporized material and the electrode and workpiece surfaces. However, it is possible for metallurgical changes to occur from the spark heating the workpiece surface [8].Using this method; conductor or semiconductor materials can be machined. The advantage of this technique is that it does not need to apply mechanical force and it is indifferent to material hardness. Material removal is mainly a thermal process, and heat treatment is not needed subsequent to the machining operation. EDM is a complex process that includes many input and output parameters [9]. In this research, the impact of input parameters on output parameters in the machining of NiTi shape memory alloy has been investigated. The discharge current, pulse-ON-duration, gap voltage, electrode polarity, electrode material, type of dielectric and the method of flushing are the input parameters that are adjusted prior to the machining operation. The output parameters include the material removal rate, surface roughness, tool wear rate and the machining precision. Selecting the optimum values for the off-line input parameters has a significant impact on the off-line output parameters, which is considered in the present investigation. So far, numerous research works have been carried out on the machining of NiTi SMAs by the EDM process. In 2004, Schvermann and Thisen conducted some research on the electrical discharge machining of nickel-titanium alloy using tungsten and copper tools and concluded that by changing the current and voltage, the depth of cracks and surface roughness can be affected [10]. In 2007, Chen et al. studied the effect of machining on Ni-Al-Fe alloy and found out that material removal rate is inversely related to the alloy's melting point and thermal conductivity. They also investigated the impact of MRR on surface roughness and recast layers [11]. In this research, the impacts of input parameters of the EDM process performed on NiTi alloy using graphite tools and de-ionized water as the dielectric on the output parameters are evaluated.

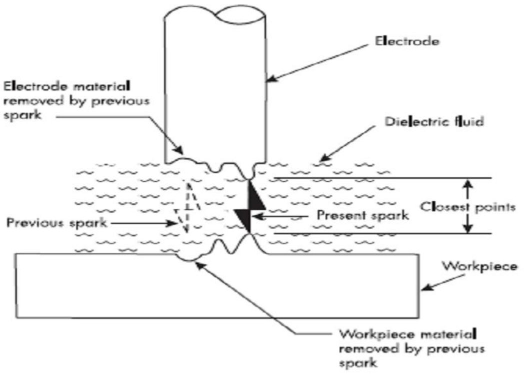

Figure 2. Principles of material removal by the EDM process [8]

2. Test Equipment and Method

The EDM specimens were performed on a die-sinking EDM machine model type 204-H, made by Tehran Ekram Co. in Iran.fig.3

Figure 3. EDM machine (model: 204H)

The workpiece material is NiTi60, with a density of 6.45 gr/cm^3. The samples have been wire cut as plates from raw materials with dimensions of 40 × 50 mm, and then they have been grinded. Table 1 shows the mechanical and physical properties of NiTi60 material. The tools used in this research are made of graphite with dimensions of $\varphi = 8 \times 40$ mm . To avoid the problem of workpiece and tool surface not being parallel, and to consider the impact of surface roughness of tools on workpieces, the surfaces of all the tools were machined and grinded using abrasive grinding. To avoid the changes of test conditions, all the tests were performed in one day. To raise the accuracy of the tests and to prevent the effect of oil-based dielectrics in reacting with the workpiece surface, de-ionized water with an EC of less than 1ms (micro-Siemens) has been used in this investigation. A constant spray type flushing system was used in all the experiments. To measure the volumes of material removed from the workpiece and tool, an 'AND' balance (model: GR-300) with a precision of ±0.0001 gr was employed (Fig.4). The 'Mahr' roughness measuring instrument (model: M300-RDI8) was used to measure the surface roughness of the workpiece.

Figure 4. 'AND' balance (model: GR-300) used for weight measurements

Table 1. Mechanical and physical properties of Nitinol-60 [12]

Density	6.45 G/cc
Tensile strength, ultimate	754 - 960 Mpa
Tensile strength, yield	560 Mpa
Elongation at break	15.5 %
Modulus of elasticity	75.0 Gpa
Poissons ratio	0.300
Shear modulus	28.8 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
Solidus	1240 °C
Liquids	1310 °C
Nickel, Ni	55.0 %
Titanium, Ti	45.0 %

3. Design of Experiments

Among the effective factors of an experiment, some are very important and the rest have lesser effects. By using the design of experiment, we are able to obtain some information regarding the factors that have a significant impact on the response; and from a large number of parameters, those needing further research can be selected. The controllable input parameters can be systematically altered and their impacts on output parameters can be evaluated and discussed. In this investigation, the Taguchi's design of experiment method has been employed as one of the strongest techniques of design and analysis of experiments [13]. To optimize the number of experiments and to generalize the results to all the levels under investigation, the orthogonal array of LI8 ($2^1 \times 3^3$) has been used. There are 18 experiments and 4 factors in this research. The factors or input parameters of this experiment include the current, voltage, pulse-ON-duration and pulse-OFF-duration. In this research, the voltage factor has two levels and the other factors have three levels. The lowest and highest values of discharge current were considered as 10A and 20A, respectively; because at discharge currents less than 10A, material removal rate is low, and at currents higher than 20A, surfaces with acceptable qualities are not obtained. With regards to equipment capacity, the voltages used in this research were 80V and 250V. Pulse-ON-durations of 35, 50 and 100 µs were chosen. At durations longer than 100 µs, flushing intensity diminishes and adversely affects the quality and rate of material removal. Pulse-OFF-durations of 30, 70 and 200 µs have been chosen. The design factors and selected levels for each one of the test parameters have been listed in Table 2. The Minitab® 16.1.1 software program has been used for process analysis. The machining operation has been carried out at constant times, and the material removal rate has been determined by measuring the difference between workpiece weights before and after the machining process. Material removal rate (mm^3/min) is determined from Eq. 1.

$$MRR = \frac{(W_1 - W_2)}{\rho_w \times t} \times 10^3 \qquad (1)$$

In this relation, MRR is the volumetric material removal rate (mm^3/min), w_1 and w_2 are the workpiece weights before and after machining, ρ_w is the density of NiTi60 shape memory alloy, and t is the machining time (min). The tool wear rate (mm^3/min) is obtained from Eq. 2:

$$TWR = \frac{(T_1 - T_2)}{\rho_T \times t} \times 10^3 \qquad (2)$$

In this relation, TWR is the tool wear rate (mm^3/min), T_1 and T_2 are the tool weights before and after machining, ρ_T is the density of graphite tools, and t is the machining time (min).The electrode wear rate (EWR) is obtained from Eq. 3.

$$EWR = \frac{TWR}{MRR} \times 100 \qquad (3)$$

TWR: volume of material removed from the tool (mm^3/min)

MRR: volume of material removal from the workpiece (mm^3/min)

EWR: electrode wear rate (%)

Table 1. Input parameters and selection levels

Factors		Levels	
Gap voltage (V)	30	250	-
Discharge current (A)	10	15	20
Pulse duration (µs)	35	50	100
Pause duration (µs)	30	70	200
Electrode	Work piece (-)	Tool (+)	
Dielectric	De-ionized water		

4. Output Parameters of the EDM Process

4.1 Analysis of Material Removal Rate

Material removal rate is proportionate to the amount of consumed power. Research has shown that in iso-frequency circuits, power is obtained from Eq. 4 [14].

$$P = \frac{V_{sp} I_{sp} (T_i - T_d)}{T_i + T_0} \qquad (4)$$

The performed tests have indicated that with regards to Eq. 4, for most alloys, the material removal rate increases with the increase of discharge current (Isp), reduction of pulse-OFF-duration (T_0), reduction of discharge delay (T_d) and the increase of pulse-ON-duration. The effects of discharge current, voltage, pulse-ON-duration and pulse-OFF-duration on material removal rate have been illustrated in Fig. 5 for the NiTi SMA.

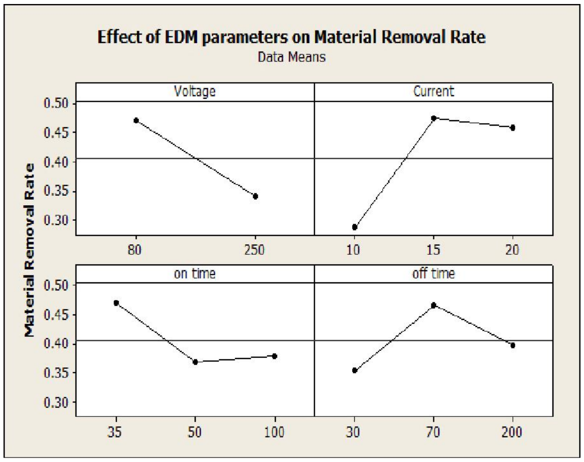

Figure 5. Impact of input parameters of the EDM process on the MRR of NiTi SMA

As is shown in Fig. 5, discharge current has the largest effect on material removal rate in NiTi SMAs. With the increase of discharge current, the amount of energy discharged with each pulse increases and a larger amount of workpiece material melts and evaporates. With the increase of discharge current up to 15 A, the rate of material removal for NiTi SMA using graphite tools has an ascending trend, and beyond 15A, it declines a little. The effect of voltage on MRR indicates that with the increase of voltage, material removal rate diminishes. With the increase of pulse-ON-duration from 35 to 50µs, MRR is reduced; and a further increase of pulse-ON-duration from 50 to 100µs, leaves little effect on the rate of material removal. In principle, with the increase of pulse-ON-duration, the amount of pulse energy (obtained from Eq. 5) increases, and consequently, the material removal rate should increase; but this didn't happen for NiTi SMA using graphite tools.

$$W = V_{SP} . I_{SP} . (T_i - T_d) \qquad (5)$$

The increase of pulse-OFF-duration to 70µs leads to the increase of MRR; however, the material removal rate diminishes beyond the 70µs point. Fig. 5

shows that the minimum and maximum rates of material removal are obtained at pulse-OFF-durations of 30 and 70µs, respectively, which could be attributed to the eradication or the preservation of the plasma channel.

4-2-Analysis of Tool Wear Rate

According to Fig. 6, the most influential parameter on graphite tool wear in the machining of NiTi alloys is the discharge current. The increase of discharge current leads to the increase of spark energy and causes the tool to melt more. There is a linear relationship between discharge current and tool wear. With the increase of pulse-ON-duration up to 50µs, graphite tool wear diminishes, and after 50µs, it increases with a mild slope.

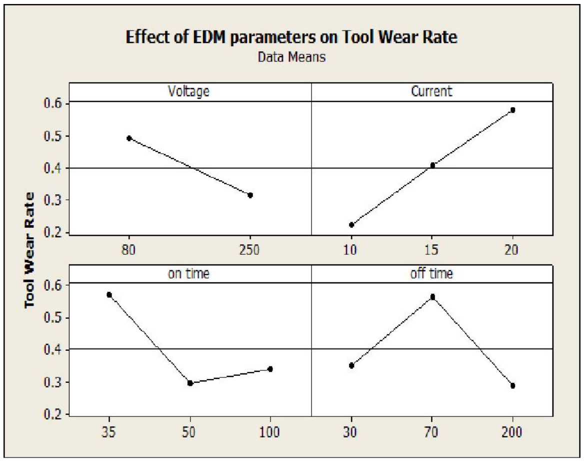

Figure 6. Impact of input parameters of the EDM process on graphite tool wear

With the workpiece and tool attached to the negative (cathode) and positive (anode) poles of the apparatus, respectively, when the pulse is initially turned on, the plasma channel diameter is small, and the flow of electrons from the negative to positive pole results in the tool wear. With the increase of pulse-ON-duration, the plasma channel diameter gradually increases, and the positive ions (with sizes 1847 times larger than electrons) become more active. This gradually reduces the movement of electrons towards the tool; and as a result of less energy and heat reaching the tool, the amount of tool wear diminishes. Therefore, with the increase of pulse-ON-duration in the machining of SMAs using graphite tools, tool wear rate diminishes. Another parameter that affects tool wear is voltage. The increase of voltage from 80 to 250V results in the reduction of tool wear rate. With the increase of pulse-OFF-duration from 30 to 70µs, the tool wear rate exhibits an ascending trend and increases, and as the pulse-OFF-duration increases further from 70 to 200µs, the tool wear rate declines after reaching a maximum value. With the increase of pulse-OFF-duration, flushing improves and a new plasma channel forms, which at the onset of spark, has a strong material removal power on the tool.

5. Analysis of Electrode Wear Rate

Fig. 7 demonstrates the effect of discharge current, voltage, pulse-ON-duration and pulse-OFF-duration on the electrode wear rate in the machining of NiTi SMA using graphite tools and de-ionized water as the dielectric. With the increase of pulse-ON-duration, tool wear rate decreases and the volume of material removed from the workpiece increases. In the EDM process with positive polarity, when the pulse-ON-duration is short, the material removal mechanism is the flow of electrons from cathode (workpiece) to anode (tool), which causes more wear on the positive end (the tool). But with the increase of pulse-ON-duration, as a result of plasma channel expansion, the flow of positive ions from tool (positive pole) to workpiece (negative pole) becomes easier and tool wear diminishes. The increase of discharge current up to 15A causes a reduction in the electrode wear rate, and then with the further increase of discharge current to 20A, the electrode wear rate increases as well. The increase of voltage also causes the electrode wear rate to increase. Pulse-OFF-duration is another parameter that affects the electrode wear rate. With the increase of pulse-OFF-duration, electrode wear rate decreases, which is due to the lack of electrical discharge.

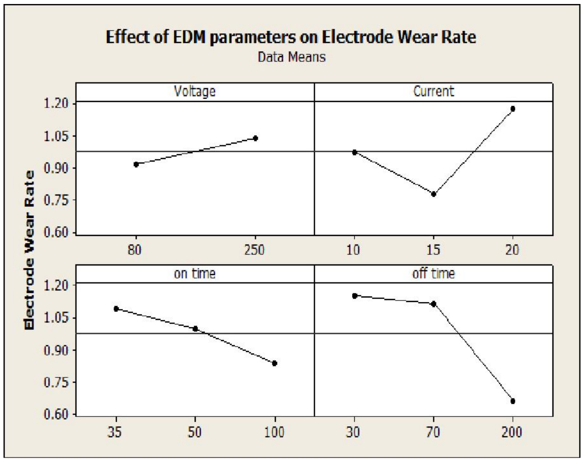

Figure 7. Impact of input parameters of the EDM process on electrode wear rate

6. Analysis of Surface Roughness

Fig. 8 shows the effects of input parameters of the EDM process on the surface roughness of NiTi shape memory alloy. Discharge current, pulse-ON-duration and pulse-OFF-duration greatly affect the surface roughness; while the impact of voltage changes on surface roughness is negligible. The increase of discharge current leads to the increase of spark energy and consequently, the reduction of surface roughness. In the iso-pulse circuit, the amount of spark energy is obtained from Eq. 5.

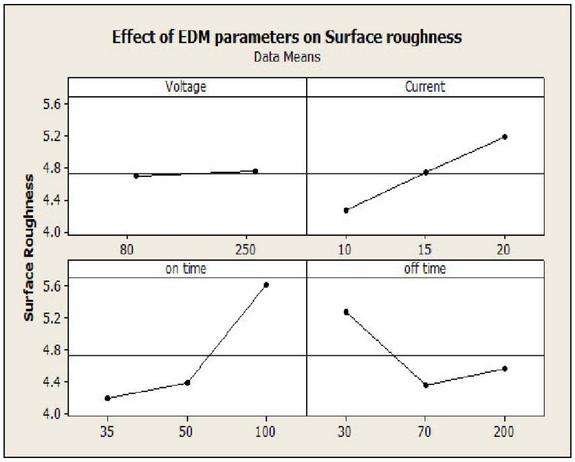

Figure 8. Impact of input parameters of the EDM process on surface roughness of NiTi SMA

In the machining of NiTi SMA using graphite tools and de-ionized water, the increase of voltage has little effect on surface roughness. The increase of pulse-ON-duration up to 50µs doesn't have much of an impact on the surface roughness of the workpiece; however, with further increase of pulse-ON-duration to 100µs, because the diameter of plasma channel increases and the protons, which are larger than electrons by 1837 times, hit the workpiece, the surface roughness of the workpiece diminishes. The increase of pulse-OFF-duration leads to the increase of surface roughness.

Figure 9. Surfaces of machined workpieces

Conclusion

In this research, the effects of input parameters of electrical discharge machining including the discharge current, pulse-ON-duration, voltage, pulse-OFF-duration, de-ionized water and graphite tools on the output parameters of the process such as tool wear rate, material removal rate, surface roughness and electrode wear rate were analyzed and evaluated for NiTi shape memory alloy. The Taguchi's method and LI8 orthogonal array were employed for the design of experiment. The obtained results indicate that the most influential parameter on the increase of material removal rate is the discharge current. With the increase of discharge current, due to the increase of spark energy, both the MRR and TWR increase. Another effective factor is the pulse-OFF-duration, whose increase up to an optimal value, results in the increase of material removal rate and tool wear, and whose further increase past the optimal value leads to the reduction of the latter parameters. The maximum rate of material removal for NiTi SMA is achieved with a discharge current of 15A, voltage of 80V, pulse-ON-duration of 35µs and pulse-OFF-duration of 70µs. With the increase of pulse-ON-duration up to 50µs, the MRR and TWR both decrease, and as the pulse-ON-duration in increased from 50 to 100µs, the MRR and TWR also increase as a result of the expansion of plasma channel diameter. The minimum rate of graphite tool wear is achieved with a discharge current of 10A, voltage of 250V, pulse-ON-duration of 50µs and pulse-OFF-duration of 30µs. The increase of voltage results in the reduction of material removal rate and tool wear rate. The increase of voltage and discharge current up to 15 A leads to the reduction of electrode wear rate and consequently, the increase of material removal rate. The maximum value of electrode wear rate in the machining of NiTi SMA is achieved with a discharge current of 20A, voltage of 250V, pulse-ON-duration of 35µs and pulse-OFF-duration of 30µs. Surface roughness diminishes with the increase of discharge current and pulse-ON-duration, due to the intensification of spark energy. The maximum degree of surface roughness in the machining of NiTi SMA is achieved with a discharge current of 10A, voltage of 80V, pulse-ON-duration of 35µs and pulse-OFF-duration of 70µs.

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