Australian Journal of Basic and Applied Sciences, 6(12): 218-225, 2012
ISSN 1991-8178

Investigation of EDM Parameters on Surface Roughness and Material Removal Rate of NiTi60 Shape Memory Alloys

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Abstract: Considering the importance of titanium alloys in aerospace, automobile and medical industries, the impact of electrical discharge machining (EDM) on smart NiTi60 alloy has been reviewed in this research. In view of the high competition that exists among various industries to lower the time, cost of production, and improve the quality, the parameters of material removal rate (MRR) and tool wear rate (TWR) are highly significant. In this research, the impact of process input parameters such as pulse on time, pulse off time, discharge current (A) and gap voltage (V) on output parameters such as tool wear rate, material removal rate and surface roughness (SR) has been investigated. For the design of experiments (DOE), the Taguchi's method, LI8 orthogonal array and the Minitab@16.1.1 software have been employed. The experiments were performed in the voltage range of 80-250V and discharge current range of 10-20A.The obtained results indicate that with the increase of voltage and discharge current, the tool wear, workpiece wear and surface roughness increase. Also with the increase of pulse on time, the tool wear increases up to a certain point, and decreases afterwards, but the material removal rate and surface roughness diminish. The results also show that as the pulse off time increases, the tool wear rate, material removal rate and surface roughness diminish.

Key words: Electrical discharge machining; Shape memory alloys; Smart materials; Brass tool; De-ionized water; Pulse off time; Pulse on time

INTRODUCTION

Metals are characterized by physical qualities such as tensile strength, malleability and conductivity. In the case of shape memory alloys, we can add the anthropomorphic qualities of memory and trainability (Cimpri c Darjan, Janez Dolin sek, 2007). Shape memory alloys (SMAs) are a fascinating group of metals that have two remarkable properties: the shape memory effect, and superelasticity (Duerig, T.W., *et al*., 1990; Otsuka, K., and C.M. Wayman, 1998). Shape memory refers to the recovery of shape after apparent permanent deformation (induced at relatively cold temperatures) by heating the metal above a characteristic transformation temperature (often near room temperature). Superelasticity refers to the isothermal recovery of relatively large strains during a mechanical load-unload cycle that occurs at temperatures above a characteristic transformation temperature. Shape memory alloys exhibit the so-called shape memory effect. If such alloys are plastically deformed at one temperature, they will completely recover their original shape when they are raised to a higher temperature. During shape recovery, these alloys can produce a displacement or a force, which is a function of temperature. In many of these alloys, a combination of force and displacement can be produced. We can make metals change shape, change position, stretch, contract, expand, bend or turn, with heat as the only activator. Products with shape memory property enjoy the following characteristics: large force produced during shape change, large movement with small temperature change, high permanent strength, process is simple to implement, no special tools are required, many possible shapes and configurations, and only heat is needed to do the job (Shape-Memory Alloys – Metallurgical, 1984). Many of these alloys, although scientifically interesting, contain precious metals, or they only possess useful properties as single crystals, and practically cannot be used in commercial applications. A few alloys, however, have emerged as commercially viable options for the fabrication of novel devices. These include certain copper alloys (CuAlZn), nickel-titanium-based alloys, such as near-equiatomic NiTi (known as Nitinol) and some ternary alloys such as NiTiCu and NiTiNb. To date, it is fair to say that NiTi-based SMAs have the best memory and superelasticity properties of all the known polycrystalline SMAs. The NiTi family of alloys can withstand large stresses and can recover strains of nearly 8% for low-cycle use or up to about 2.5% for high-cycle applications. This strain recovery capability can enable the design of novel devices in either a thermally active mode or an isothermal energy absorption mode. The NiTi SMAs have other advantages in terms of corrosion resistance, fatigue resistance, and biocompatibility, which make them the preferred material system for most shape memory applications being considered today (Cimpri c Darjan, Janez Dolin sek, 2007). The mentioned alloys have also been exploited in mechanical and electromechanical control systems to provide, for example, a precise mechanical response to small and repeated temperature changes (Srinivasan, A.V., D. McFarland Michel, 2001). Shape memory alloys are also used in a wide range of medical and dental applications (Anson, T., 1999). These alloys can exist in final product form in

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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 crystalline structure of austenite 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 material, however, almost looks like that of an elastomer, with '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 material in the lower temperature martensite state has a 'twinned' crystalline structure that involves a mirror symmetry displacement of atoms across a particular plane. Twin boundaries are formed, which can move easily and without causing micro-defects such as dislocations. Unlike most metals that undergo deformation by slip or dislocation movement, deformation in a twinned structure occurs through large changes in the orientation of its whole crystalline structure caused by the movement of its twin boundaries. 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 (Fig. 1) (Michelle, A., L. Daniel Schodek,).

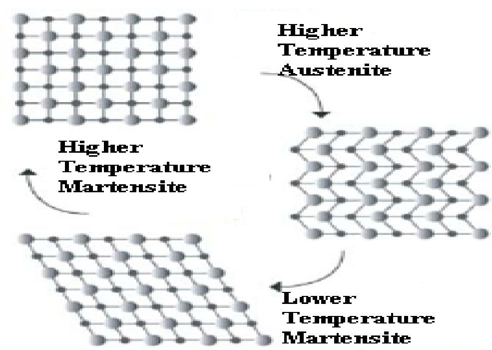

Fig. 1: Shape memory alloys

With the development of smart materials, the non-traditional machining methods such as laser machining, electrochemical machining and electrical discharge machining were studied. Due to the low cost and the availability of the electrical discharge machining process, it is used more often than the other processes. EDM is a thermal erosion process in which metal is removed by a series of recurring electrical discharges between a cutting tool (acting as an electrode) and a conductive workpiece, in the presence of a dielectric fluid. This discharge occurs in a voltage gap between the electrode and workpiece. Heat from the discharge vaporizes minute particles of workpiece material, which are then washed away from the gap by the continuously flushing dielectric fluid. There are two main types of EDM: the ram, and the wire-cut. Each are used to produce very small and accurate parts as well as large items like automotive stamping dies and aircraft body components. The largest single use of EDM is in die making. Materials worked with EDM include hardened and heat-treated steels, carbides, polycrystalline diamond, titanium, hot- and cold-rolled steels, copper, brass, and high temperature alloys. However, any material to be machined with the EDM process must be electrically conductive. In EDM, the electrode/tool is attached to a ram, which is connected to one pole, usually the negative pole, of a pulsed power supply. The workpiece is connected to the positive pole. The workpiece is then positioned so that there is a gap between it and the electrode. The EDM process removes material by creating controlled sparks between a shaped electrode and an electrically conductive workpiece. As a part of material is eroded, the electrode is slowly lowered into the workpiece, until the resulting cavity has the inverse shape of the electrode. The gap is then flooded with the dielectric fluid. Once the power supply is turned on, thousands of direct current (DC) impulses per second cross the gap, starting the erosion process. The generated spark temperatures can range from 14,000° to 21,000° fahrenheit. As the erosion continues, the electrode advances into the workpiece while maintaining a constant gap dimension. Di-electric fluid is flushed into the gap between the electrode and workpiece to remove the small particles created by the process and to prevent excessive oxidation of the part surface and the electrode. The EDM finished workpiece can exhibit several distinct layers. The surface layer will have small globules of removed workpiece metal and electrode particles adhering to it, which are easily removed. The second layer, called the recast layer, is where the EDM has altered the metallurgical structure of the workpiece. The third layer is the heat-affected zone or annealed layer. This layer has been heated but not melted (Electrical Discharge Machining,). Compared to other machining techniques, the electrical discharge machining methods capable of producing complex and intricate parts with a high degree of accuracy. This process is able to machine hard materials, which are difficult to machine by other methods.

Another advantage of EDM is its ability to machine extremely small parts. The important characteristics of the EDM process comprise the efficiency, surface quality and the undercut. The efficiency includes the rate of material removal from the workpiece and the rate of tool wear. The importance of these features depends on the conditions under which the workpiece is machined and utilized. Numerous research works have already been conducted on the machining of memory shape alloys. In 2008, Pradhar *et al*. investigated the subject of titanium micromachining and found out that the pulse-on-time and discharge current have the highest impact on the rates of material removal and tool wear. With the increase of discharge current, the spark energy increases and causes, the rate of material removal and tool wear to go up. As the pulse-on-time increases up to 10 μs, tool wear and material removal rate increase, and after reaching a maximum value, with the further increase of pulse-on-time, the material removal rate diminishes. In 2010, Rahman *et al*. examined the effects of pulse on time, pulse off time and discharge current on surface roughness, MRR and TER of Ti-6Al-4V alloy. They realized that the pulse-on-time and discharge current have the highest effect on the output parameters of spark machining [6]. In 2003, W. Theisen *et al*. investigated the machining of smart materials by copper-tungsten tool (Michelle, A., L. Daniel Schodek,). Due to the importance of using smart materials in various industries, their machining operation has a special significance. In this research, the impact of machining input parameters such as discharge current, pulse-on-time and pulse-off-time on material removal rate, tool wear rate and surface roughness is investigated for the NiTi60 shape memory alloy.

2. Experimental Equipments:

2.1. Electro-Discharge Machine:

The Electro-Discharge machine with iso-frequency generator (model: 204H made by Tehran Ekram Azarakhsh Co.) was used in the experiments. The dielectric used in the experiments is de-ionized water in the form of pressure flushing, which leaves the smallest impact on the surface of the workpiece (Fig. 2).

2.2. Workpiece:

NiTi60 shape memory alloy is the workpiece material used in the EDM process. This alloy has a high hardness value, and its machining by traditional methods is a costly, and sometimes impossible, process. The mechanical and physical properties of this material have been listed in Table 1.

Fig. 2: EDM machine, model: 204H

Table 1: Physical and mechanical Properties of NiTi60 [10]

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
Poisson's 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	60.0 %
Titanium, Ti	40.0 %

2.3. Tool Material:

Metals with high melting point and good electrical conductivity are usually chosen as tool materials for the EDM process. They should be cheap and easy to shape by conventional methods. Brass was featured as the tool material of choice in the early periods of EDM development. Although this metal is a highly stable material in sparking operations, its relatively high wear restricts its use to highly specialized applications. Brass is the tool material used in this experiment. Of every tool, 9 samples with the diameter of 8 mm and length of 40 mm were prepared, and the tool was attached to anode of the apparatus. For the surfaces of tool and workpiece to be parallel, and to include the effect of the initial roughness of tool on workpiece, all the surfaces of tool and workpiece were machined and grinded.

2.4. Weighting Balance and Roughness Measuring Instrument:

To measure the weights of the workpiece and tool after each machining run, an 'AND' balance (model: 300) with a precision of ±0.0001gr was used. Also, a 'Mahr' roughness measuring instrument (model: M300-RO18) was employed for the measurement of surface roughness (Fig. 3).

Fig. 3: Mahr surface roughness-measuring instrument (model: M300-RD18)

3. Design of Experiment:

The machining process in the EDM depends on various parameters. These parameters are divided into two groups of input and output parameters. The input parameters could be on-line or off-line. To optimize the output parameters, the on-line parameters can be controlled or changed. The off-line parameters can only be adjusted before the start of machining operation. The spark current, pulse on time, circuit voltage, tool polarity, tool material, type of Di-electric and the flushing method are some of the important input parameters that are regulated prior to machining. The input parameters during machining include the pulse off time, gap between tool and workpiece and flushing. The off-line output parameters that constitute the main results of the process include the MRR, surface roughness and tool wear. The parameters of spark current, voltage, pulse on time and pulse off time were selected as the parameters under investigation in the machining of NiTi memory shape alloy. In this research, the Taguchi's design of experiment method has been used as one of the strongest methods of design and analysis (Theisen, W., A. Schuermann, 2004). 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 comprise the current, voltage, pulse on time and pulse off time. In this investigation, the voltage factor has two levels and the other factors have three levels. The parameter types have been shown in Table 2.

The difference between tool weights and also between workpiece weights, before and after machining, has been measured with a precision of ±0.0001 gr. Material removal rate (MRR), tool wear rate (TWR) and surface roughness were selected as the output parameters of this experiment. Relations (1) to (3) express the equations corresponding to MRR, TWR and relative electrode wear (REW), respectively.

$$\mathrm{MRR} = \frac{V_W}{T} \tag{1}$$

$$\mathrm{TWR} = \frac{V_T}{T} \tag{2}$$

$$\mathrm{REW} = \frac{V_W}{V_T} \tag{3}$$

V_W: Volume removed from the workpiece (mm^3)

V_T: Volume removed from the tool (mm^3)

MRR: Material removal rate (mm^3/min)
REW: Relative electrode wear (%)
In this research, the densities of brass tool and NiTi shape memory alloy have been considered as 8.4 gr/cm^3 and 6.67 gr/cm^3, respectively.

Table 1: The machining parameters

Factors	Levels		
Gap voltage (V)	80	250	-
Discharge current (A)	10	15	20
pulse-on-time (µs)	35	50	100
pulse-off-time (µs)	30	70	200
Tool polarity	Negative		
Workpiece polarity	Positive		
Dielectric	De-ionized water		

4. Material Removal Rate (MRR):

Material removal rate denotes the volume of material removed from the workpiece in unit time. MRR depends on various properties of the workpiece material, including its melting point and latent heat. It is also influenced by the properties of tool electrodes and by geometric factors such as the shape and dimensions of the tool and workpiece. For a specific workpiece and for a tool with a defined polarity and constant Di-electric, the MRR depends on the spark current, pulse on time and pulse off time. Figure 2 shows material removal rate versus voltage, spark current, pulse on time and pulse off time. As is indicated by Figure 4, the spark current parameter has the highest impact on the material removal rate of NiTi shape memory alloy and with its increase, the MRR value increases as well. With the increase of spark current, the spark energy and consequently, the workpiece's surface temperature goes up and the rate of material removal increases rapidly. Research works indicate that for most alloys, the impact of spark energy on MRR is substantial. Based on Figure 4, the second most influential parameter on the material removal rate of NiTi shape memory alloy after the spark current parameter is the pulse off time. With the increase of pulse off time, the material removal velocity diminishes considerably. During the pulse off time, no material removal is carried out, and this time is spent for flushing and getting rid of the plasma channel, which lead to the cooling of the machining area. Pulse on time is another parameter that affects the material removal rate. With the increase of pulse on time, the rate of material removal from the workpiece increases with a mild slope, indicating that this parameter has little effect on the machining of NiTi shape memory alloy. For this alloy, the increase of pulse on time up to 100µs has provided the needed time for the plasma channel to become wider and for the positive ions to become more active as a result. As these ions attack the workpiece and discharge energy onto its surface, more of the workpiece surface melts and evaporates. Therefore, by increasing the pulse on time to 100µs, the right conditions are provided for the creation of spark. Although investigations have shown that for most alloys, the increase of voltage greatly influences the rate of material removal, for the NiTi60 material, the increase of voltage has little effect on MRR (Tomadi, S.H., *et al*., 2009; Reza Atefi, *et al*., 2012).

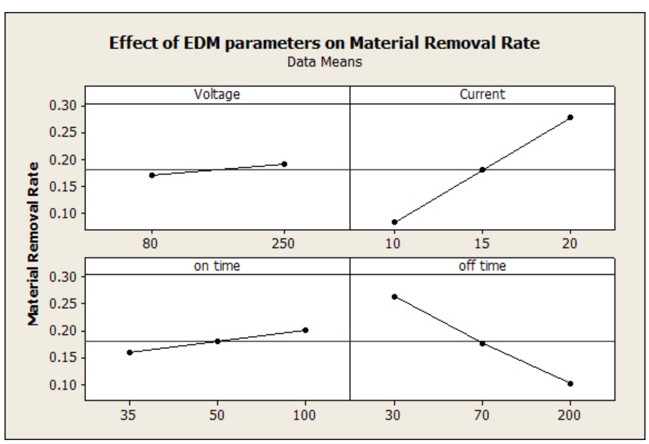

Fig. 4: Variation of material removal rate with pulse-on-time, pulse-off-time, discharge current and gap voltage

5. Tool Wear Rate (TWR):

Fig. 5 illustrates the impacts of input parameters of the machining process including the discharge current, voltage, pulse on time and pulse off time on tool wear for the NiTi60 shape memory alloy. With the increase of current in the iso-frequency circuit (independent of electrode material), the spark energy (obtained from relation (1)) increases.

$$W = V_{sp}.I_{sp}(T_i - T_d) \tag{4}$$

With the increase of spark energy, the tool surface temperature rises and causes the melting and wear of the tool. Another reason for the increased wear of the brass tool is the low melting point of brass (820-1030ºC) relative to that of the NiTi SMA (1240-1310ºC). With the increase of voltage, the wear and erosion of brass tool increases, and the voltage increase has a higher impact on TWR than on MRR. In the machining of NiTi SMA using brass tools and De-ionized water as the Di-electric, the increasing of pulse on time up to 50µs, causes a relative increase in TWR. At the pulse on time of 50µs, tool wear reaches the maximum point, and then it starts to decrease with the further increase of pulse on time; so that at 100µs, we have the lowest TWR. With the increase of pulse on time, the diameter of plasma channel gets larger and causes the energy concentration and, consequently, tool wear to gradually diminish. Another factor in the reduction of tool wear is the contamination of Di-electric. With the increase of pulse on time, the contamination of Di-electric increases and the number of sparks goes down, leading to the reduction of tool wear. Increasing the pulse off time up to 70µs causes a drastic reduction in tool wear rate during the machining of NiTi SMA using brass tools and De-ionized water; an increase of pulse off time beyond 70µs has little effect on TWR.

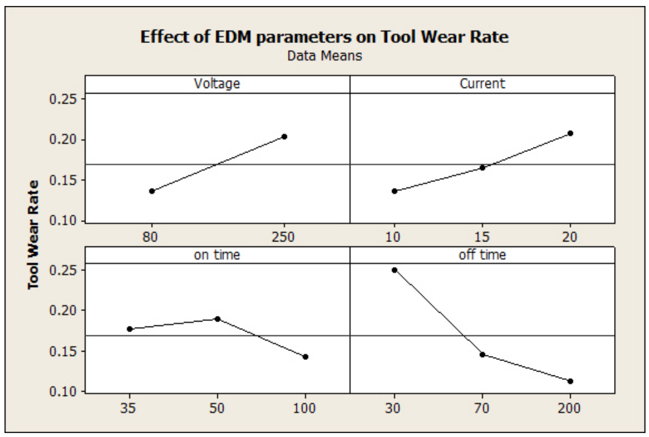

Fig. 5: Variation of tool wear rate with pulse-on-time, pulse-off-time, discharge current and gap voltage

6. Analysis of Relative Electrode Wear:

The ratio of material volume removed from the tool to material volume removed from the workpiece is called ‘relative electrode wear’, and it is expressed as a percentage. Relative electrode wear (REW) depends on discharge current, pulse on time, tool shape, type of flushing, tool material, workpiece material and the type of Di-electric. According to Figure 6, for the machining of NiTi smart material alloy using brass tools and De-ionized water, the REW percentage has diminished with the increase of discharge current. This means that, simultaneous with the increase of workpiece wear, the brass tool wear decreases. With the increase of pulse on time up to 50µs, relative electrode wear decreases slowly; and as the pulse on time increases to 100µs, the REW decreases at a more rapid pace. With the increase of pulse on time, the plasma channel gradually increases in diameter and the positive ions, which are 1837 times heavier than electrons, become more active, and the activities of smaller electrons gradually diminish; and because the tool has a positive pole, fewer number of electrons impact the tool and less energy and heat is imparted into the tool; thus, the REW of brass tool decreases, and the dimensional accuracy of the work piece goes up (Figure 7). REW increases with the increase of voltage. For the machining of NiTi SMA using brass tools, with the increase of pulse off time up to 70µs, the relative electrode wear diminishes; although for materials like tungsten carbide and steel, the value of REW increases with the increase of pulse current, and then with the increase of pulse off time up to 200µs, the REW increases as well.

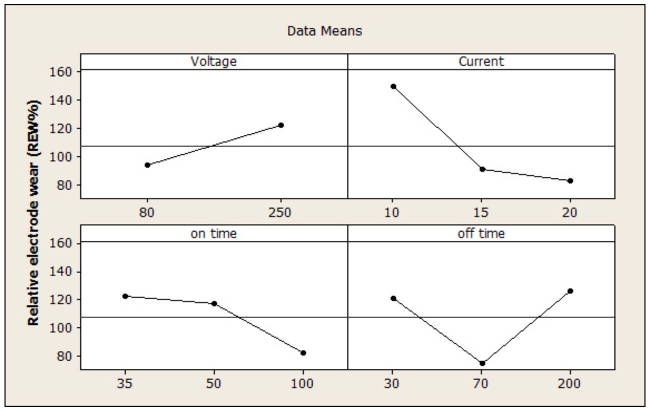

Fig. 6: Variation of relative electrode wear with pulse-on-time, pulse-off-time, discharge current and gap voltage

7. Analysis of Surface Roughness:

The impacts of discharge current, voltage, pulse on time and pulse off time on the surface roughness of samples made of NiTi60 using brass tools and De-ionized water have been illustrated in Figure 7. Pulse on time is the most effective parameter on surface roughness. With the increase of pulse on time, spark energy increases and causes the enlargement of pores created through electrical discharge on the surface of workpiece; and as a result, surface roughness increases. The spark energy in the iso-frequency circuit is obtained from relation (1). With the increase of Pulse on time, the voltage and current of spark energy increase and the surface of workpiece becomes rougher. Figure 7 shows these effects for the NiTi alloy. With the increase of pulse off time, surface pores decrease in number and surface roughness diminishes (Simul Banerjee, Debasish Mahapatro, 2008).

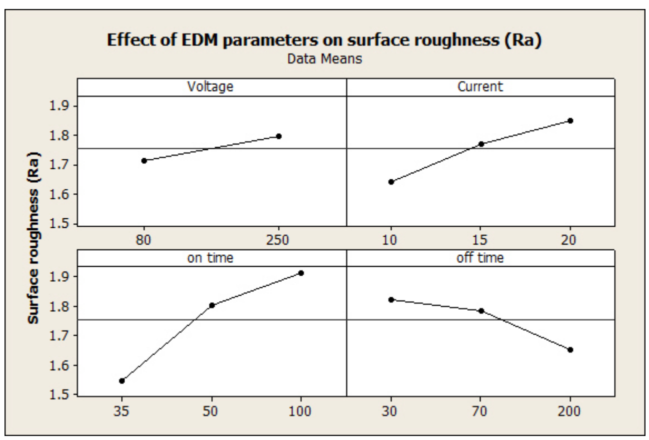

Fig. 6: Variation of surface roughness with pulse-on-time, pulse-off-time, discharge current and gap voltage

Conclusion:

In this research, the impacts of the input parameters of the EDM process including the discharge current, pulse on time, pulse off time and voltage on the output machining parameters of NiTi shape memory alloy obtained by using brass tools and De-ionized water were investigated. For the design of experiments, the Taguchi's method and theLI8 orthogonal array were employed. The experimental results indicate that:

1- The increase of discharge current and voltage causes the pulse energy to increase and as a result, the material removal rate and tool wear increase.

2- The increase of pulse on time from 35 to 50µs causes the tool wear rate to increase. With a further increase of pulse on time from 50 to 100µs, the tool wear rate diminishes, but the material removal rate goes up.

3- The increase of pulse off time causes both the material removal rate and tool wear to decrease.

4- with the increase of voltage, relative electrode wear increases and consequently, material removal rate diminishes. With the increase of discharge current and pulse on time, relative electrode wear decreases and as a result, material removal goes up.

5- With the increase of voltage, discharge current and pulse on time, spark energy builds up and causes the surface roughness of NiTi60 SMA to increase.

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