Investigation of Wire Electro Discharge Machining of Nickel-Titanium Shape Memory Alloys on Surface Roughness and MRR

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Abstract: Shape memory alloys are kind of smart materials, which have distinctive properties and are superior in compare with other alloys. Severe reactions to thermodynamic and mechanical parameters and ability to return to their original shape make these alloys distinctive from other alloy regarding machining ability. Since these alloys have a very useful application in various fields such as aerospace, automobile, medicine, dentistry, the present paper surveys the effect of wire electrical discharge machining on them. Surface roughness and material removal rate are the most important parameters of machining which influence product quality and machining time. Reducing surface roughness improves fatigue resistance, corrosion and wear resistance of work piece. Increasing the removal rate and reducing machining time decline the production costs and increase production. The present research seeks to investigate the effect of wire electrical discharge machining parameters on surface roughness and removal rate of NiTi60. Results reveal that increasing current pulse, pulse on-time and wire speed increase surface roughness and material removal rate.
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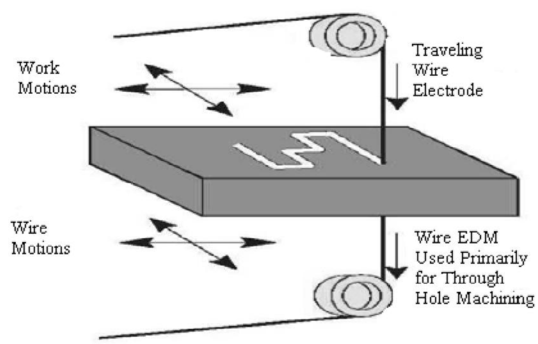
1. Introduction

The cost reduction, increasing production rate, low surface roughness and high dimensional accuracy are the most important objectives in machining processes. These objectives enjoy a high importance for expensive materials with low machining ability. New developments in the field of material science have led to new engineering metallic materials, composite materials, high tech ceramics and shape memory alloys, having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity so that they can readily be machined by spark erosion. Traditional machining technique is often based on the material removal using tool material harder than the work material and they are unable to machine economically. At the present time, electrical discharge machining (EDM) is a widespread technique using in industry for high precision machining of all types of conductive materials such as: metallic alloys, metals, graphite, or even some ceramic materials of whatsoever hardness. EDM technology has been increasingly used in tool, die and mould making industries, for machining of heat treated tool steels and advanced materials requiring high precision, complex shapes and high surface finish [1, 2]. Development of new advanced engineering materials and need for precise and flexible prototypes and low-volume component production have made wire electrical discharge machining (WEDM) an important manufacturing process to meet such a demand [3]. The three electrical discharge-machining methods, wire, ram, and small whole EDM all work on the principle of spark erosion [4]. As its name represents, material is eroded from the work piece by electrical discharges that create sparks. Ram EDM, also known as conventional EDM, sinker EDM, die sinker, vertical EDM, and plunge EDM are generally used to produce blind cavities. In ram, EDM sparks jump from the electrode to the workpiece. This causes material to be removed from the work piece. Wire EDM uses a traveling wire electrode that passes through the work piece. The wire is monitored precisely by a computer-numerically controlled (CNC) system Figure 1 [5]. The spark theory on a wire EDM is basically the same as that of the vertical EDM process. In wire EDM, the conductive materials are machined with a series of electrical discharges (sparks) that are produced between an accurately positioned moving wire (the electrode) and the work piece. High frequency pulses of alternating or direct current is discharged from the wire to the work piece with a very small spark gap through an insulated dielectric fluid (water). Many sparks can be observed at one time. The volume of metal removed during this short period of spark discharge depends on the desired cutting speed and the surface finish required

[6, 7]. Between the wire and the work piece is a shield of demonized water called dielectric. Pure water is an insulator, but tap water usually contains minerals that cause the water to be too conductive for wire EDM. To control the water conductivity, the water goes through a resin tank to remove much of its conductive elements. This water is called demonized water. The work piece and the wire represent positive and negative terminals in a DC electrical circuit, and are always separated by a controlled gap, constantly maintained by the machine. This gap must always be filled with a dielectric fluid, in this case demonized water, which acts as an insulator and cooling agent. When sufficient voltage is applied, the fluid ionizes. Then a controlled spark precisely erodes a small section of the work piece, causing it to be melted and vaporized. These electrical pulses are repeated thousands of times per second [5]. Shape memory alloys (SMAs) exhibit unique thermal and mechanical properties that have been extensively studied for over fifty years. While they have been well studied, a push for industrial and commercial applications has only begun to grow in the last 15 to 20 years. The ability of SMAs to recover large strains under thermal and mechanical loading has led to the development of many applications in the biomedical, oil, and aerospace industries [8, 9, 10, 11]. The aerospace industry, on the other hand, has taken a closer look to use SMAs for thermally activated actuator applications [12]. Shape memory alloys have wide range of usage such as free recovery, constrained recovery, actuation recovery and super elastic recovery [13]. Characteristic for shape memory materials is an unconventional, unique correlation of strain, stress and temperature, which is based on crystallographic reversible thermo elastic martenstic transformation. The low temperature and the high temperature phases are, analogous to steel technology named martensite and austenite. The transformation start and finish temperatures are A_S (austenite start) and A_f (austenite finish), and M_S (martensite start) and M_f (martensite finish) during heating and cooling, respectively. The temperature-triggered transformation can be accompanied by unusually large strain; if external forces constrain the deformation, the stress can strongly increase (capability to perform mechanical work). At temperatures above A_f but below Md (the highest possible temperature for the formation of stress-induced martensite), the reversible martensitic transformation can be triggered by an increase of stress level. In this case, an unusual large strain accompanied by very small additional stress increase is possible (pseudo elasticity). When unloaded, transformation and shape change in the reverse direction and order take place. Above M_d, plastic transformation would occur before the onset of the martensitic transformation. When martensite is deformed and heated to the austenitic state, the material returns to the shape it had before the pseudoplastic deformation [14]. The pseudoplastic deformation is characterized not by gliding and generation of dislocations but by movement of twin boundaries thereby reducing the number of different martensitic variants. Upon subsequent cooling, the shape remains unchanged. This phenomenon is known as one-way shape memory effect since there is a shape change during heating only and not during cooling. It is a natural crystallographic property of shape memory materials (Fig. 2). Strain values up to 8% can be recovered in polycrystalline NiTi alloys. The most well known shape memory alloy is NiTi with about equiatomic composition. The transformation temperatures decrease strongly with increasing Ni content. The high-temperature phase (austenite) has an ordered BCC structure; the low-temperature phase (martensite) has an ordered monoclinic structure [15].



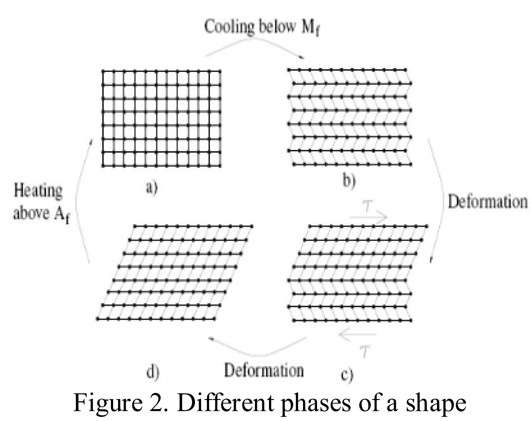


Figure 2. Different phases of a shape memory alloy [12]

Numerous studies have been made for improving machining ability of these materials. Gokler and Ozanozgu conducted some research about three types of steel to improve the surface roughness

[16]. Their research showed that increase of work piece thickness causes more stability and less surface roughness. Kanlayasiri and Boonmung surveyed the effect of pulse on time, pulse off time, pulse current and tension wires on roughness of surface of steel DC53. They concluded that the pulse on time and current are variables, which influence surface quality [17]. Han and Jiang examined the effect of discharge current on surface roughness of steel Cr12 [18]. They conducted the research using different discharge currents and pulse times. Effect of machining parameters such as current, wire speed, pulse on time on surface roughness and effect of current and pulse on time on MRR for NiTi60 alloy has been investigated in their research.

2. Experiments

2.1 Materials

Due to different melting point, evaporation and thermal conductivity, different materials show different surface quality and MRR at the same conditions of machining. NiTi60 is the material, which has been used in the experiments. NiTi considers as a smart materials. The main features of this material are high corrosion resistance, high electrical resistance, good mechanical properties, fatigue resistance, detection and environmental changes [19]. One of the best options to choose NiTi60 for machining is WEDM as it is heat process and toughness of materials doesn't affect it. The work piece dimensions are 47.3 ×30 × 13.3 mm, which was cut in dimensions of 3 × 13.3 ×47.3 mm for different experiments conditions. The mechanical properties of this alloy are shown in table 1.

Table 1. Mechanical and physical properties of Nitinol-60

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
Specific heat capacity	0.320 J/g-°c
Thermal conductivity	10.0 W/m-k
Melting point	1240 - 1310 °C

2.2 Test equipment

WEDM, model ONA, series PRLMAS250 was used for experiments. Regarding fixed dimensions of workpiece, machining velocity obtains by measuring machining time through stopwatch and dividing length of workpiece by cutting time. To measure the surface roughness Perthometer M1 made by Mahr Company has been used. Surface roughness has been measured at the longitudinal direction of cutting and perpendicular on it and the average is considered as the surface roughness. To measure machining volume, AND scales, model GR300 with 0.0001 accuracy has been used.

3. Design of experiments (DOE)

Among effective factors in a test, some of them are very important and others are less effective. By using design of experiments, we can obtain some information about factors which effects majorly on responses and select those parameters which need further studies among the large number of them. Manageable input parameters can be changed systematically and their effect on the output parameters can be discussed and evaluated. Taguchi method has been used in the present study as one of the strongest methods of designing and analyzing experiments. WEDM has different input parameters. Variables during the test are pulse current, wire speed and pulse on time [20, 21]. Wires diameter, tension, and other parameters are considered constant. Table 2 shows the test variable parameters. Minimum and maximum amount of discharge current are 1A and 2.5A respectively. Rupture occurs when Amps increase more than 2.5A for 47.3mm of cut length. Pulses on time were chosen 2, 4 and 6 µs. At higher pulse on time, flashing decreases and surface quality and material removal rate are affected. Wire speeds were chosen 0.8, 0.5 and 1.5 mm/s. If wire speed increases more than 1.5 mm/s, the wire will rupture. Material removal rate can be achieved by using weight difference of workpiece before and after machining. Material removal rate is obtained by equation (1) based on gr/min. In this equation, MRR is Material Removal Rate based on gr/min and W_1 and W_2, are weights of workpiece before and after machining.

$$\text{Material Removal Rate (MRR)} = \frac{W_1 - W_2}{T} \quad (1)$$

W_1= initial weight of the workpiece (gr)
W_2= final weight of the workpiece (gr)

Table 2. The operational parameters of WEDM

Wire electrode	Brass		
Current (A)	1	2	-
Pulse on time (µs)	2	4	6
Wire speed (mm/min)	0.5	1	1.5
Flushing pressure (kg/cm^2)		5	
Dielectric		De-ionized water	

4. Evaluation of wire speed, current and pulse on time on surface roughness

Figures 3 and 4 show the effects of input parameters of WEDM including wire speed pulse current and pulse on time on surface roughness (Ra). Figure 3 show that increasing wire speed and discharge current grow surface roughness. Effect of pulse on time on surface roughness has been shown in figure 4. By increasing discharge current and pulse on time, spark energy, which follows equation 2, is increased and volume of craters on the surface of the workpiece is increased too. Also, surface temperature of workpiece is risen; therefore, larger holes from evaporation and melting are created. Increase of off time decreases surface roughness. Growth of off time reduces the surface temperature by increasing gap flashing. There has been a growth in sparks caused by increasing of off time hence machining velocity is decreased.

$$\Delta E = V_D \times K \times T_{on}^2 \qquad (2)$$

ΔE= Spark energy
T_{on}= Pulse on time
V_D = Gap voltage
K= Current slope increasing

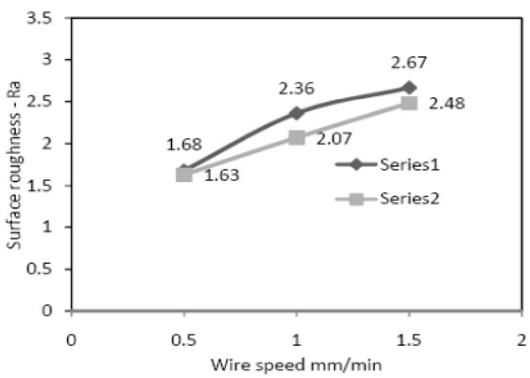


Figure 3. Surface roughness at various wire speed

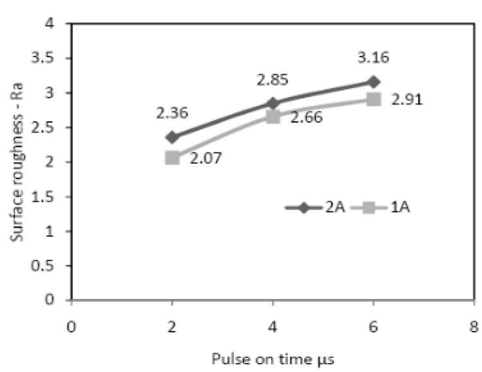


Figure 4. Surface roughness at various pulse on time

5. Evaluation of discharge current and pulse on time on MRR

Figure 5 shows the effect of pulse on time and pulse current on MRR of NiTi alloy by WEDM method. With increasing current and pulse on time in a constant feed of wire, material removal rate increases. When pulse current increases, the spark energy and surface energy increase and melting and MRR increase rapidly at the same time. When pulse current and pulse on time increase, the number of positive ions attacks on workpiece's surface increase too; moreover workpiece's temperature and melting and consequently MRR increase. Pulse current increasing is allowed to a special range, as the wire increasing is being higher than that range subsequently lead to wire tearing. Pulse current can be increase by changing some parameters such as wire speed, wire tension, wire diameter and dielectric pressure.

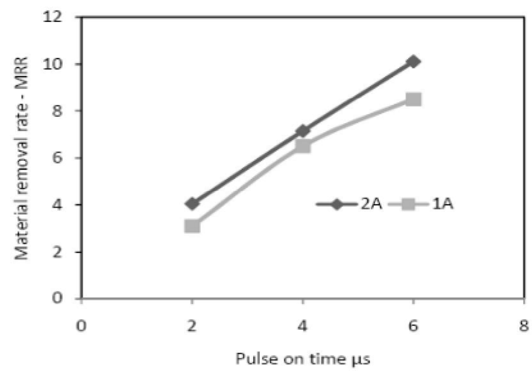


Figure 5. MRR at various pulse on time

6. Effects of various parameters of WEDM on morphology of surface

In this section, cutting surface of NiTi60 by WEDM studies regarding spark behavior and craters on workpiece. In this regard, SEM (Scanning Electronic Microscope), model AIS-2100, made in Seron Company is used. Craters create on the cutting surface at the same time when making spark in a gap between the electrodes. With regard to the optional parameters, different sizes of crater and margin in the shape of rim made by re-melting are existed. Depending on the process, lifting model via volatile and formation of extremely small collapse are the main factor to penetration of wireless materials on the workpiece's surface. Considering the surface morphology of different components and thickness of crater edge, penetration of wireless materials can be seen by microscopic images (Figure 6 to 8). According to the figures craters make over Lap phenomenon by consecutive sparks in small time. Concentration on cutting surface increases when collapse isolation percentage on the wire increased by evaporation mechanism. When power increases due to increase in energy density of pulses and when surrounding temperature increases due to increase in percentage of evaporation, craters should have fewer nesses. However, due to the MRR and increased depth of crater and the higher surface roughness, energy density is raised.

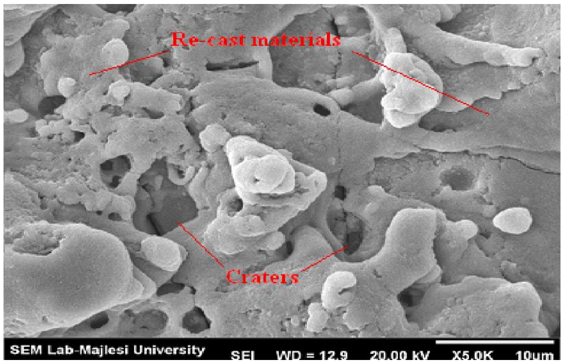


Figure 6. SEM micrograph of the WEDM surface at magnification 5000

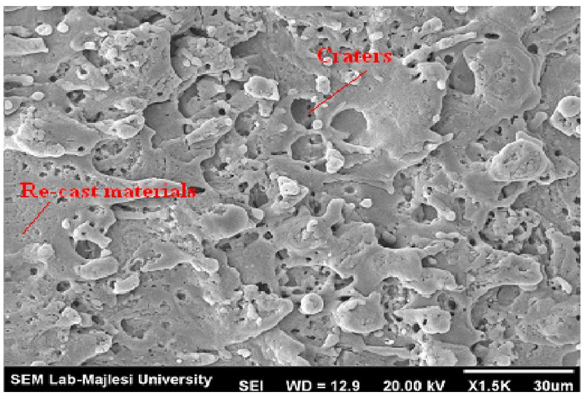


Figure 7. SEM micrograph of the WEDM surface at magnification 1500

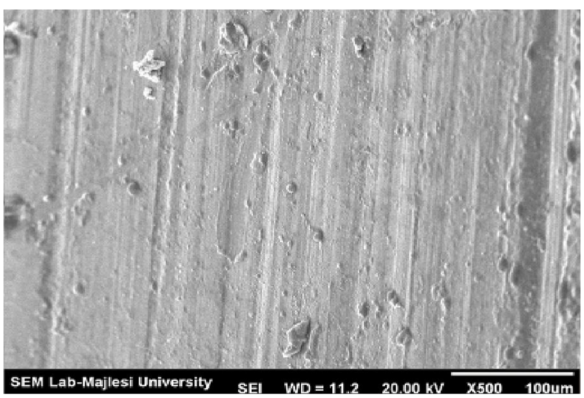


Figure 8. Cross-sectional SEM micrographs of the WEDM specimens NITI60

7. Conclusion

Capabilities of NiTi60 have been studied in the present research. For this purpose, the effect of input parameters of WEDM including wire speed, pulse current and pulse on time on surface roughness and MRR were investigated. Increase of power increases discharge energy and the number of spark which increases the temperature of workpiece and machining speed increases surface roughness rapidly. The study showed that the most affective factor in MRR of NiTi60 alloy is pulse current so that when it increases, MRR increases too. Other factors that increase MRR are wire speed and pulse on time, which increases surface roughness. According to the wire tension and diameter, increases of pulse current are allowed to a special range and over than that range will tears the wire. As cutting process by WEDM is electro thermal, with large number of sparking in NiTi60, lots of craters formed on this smart alloy and due to penetration of isolated materials separated from wire cut on the craters, alloying is done by recast materials. By fast cooling of the melt, a layer with 10-20 µm thickness is formed on the surface of NiTi; this alloy is no more NiTi and has different phases from CuZn, Nio and Cu_2O. These components changed physical and mechanical properties of cutting surface in compared with centre of workpiece.

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