Analysis of Tool Kind Effect on Material Removal Rate in Nickel Titanium Smart Alloy

Esmaeil Abedi[1], Saeed Daneshmand[2], Reza Hessami[3]

[1,2] Department of Mechanical Engineering, Majlesi Branch, Islamic Azad University, Isfahan, Iran

[3.] Department of Mechanical Engineering, Roudbar Branch, Islamic Azad University, Roudbar, Iran
e.abdi@iaumajlesi.ac.ir

Abstract: Nickel-Titanium Alloys is a kind of smart materials that are used in medicine, aerospace and other industries. Because of the strength and hardness, EDM method is used for machining of this alloy. Electrical discharge machining process is most practical non-traditional machining methods when toughness and physical properties of the workpiece does not affect on machining capability. This study examines the utility of copper, brass and EDM input parameters on the material removal rate and surface roughness of NiTi smart alloy. Experimental results show that tool material, the pulse current and the pulse duration are the most important effect on material removal rate and surface roughness of NiTi alloy. With increasing pulse current and pulse duration, material removal rate and surface roughness increases. Copper tools has higher material removal rate than the brass tools.
[Abedi E, Daneshmand S, Hessami R. **Analysis of Tool Kind Effect on Material Removal Rate in Nickel Titanium Smart Alloy**. *Life Sci J* 2013;10(1):944-949] (ISSN: 1097-8135). http://www.lifesciencesite.com. 147

Keywords: Nickel-titanium; Electrical discharge machining; Material removal rate; Copper electrode; Brass electrode; Surface roughness.

1. Introduction

NiTi alloy has an smart material which is composed of 40% titanium and 60% nickel. When temperature changes this alloy shows super elasticity and shape memory behavior [1]. With the development of smart materials, traditional manufacturing methods have difficulties for machining of these alloys. Non-traditional manufacturing techniques such as laser machining, electrical discharge machining and electro chemical machining are used for machining of these alloys [2]. Electro Discharge Machining (EDM) is an electro-thermal non-traditional machining process, where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark. EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. Both electrode (tool) and workpiece must be electrically conductive [3]. Its unique feature of using thermal energy is to machine electrically conductive parts regardless of their hardness; its distinctive advantage is in the manufacture of mould, die, automotive, aerospace and other applications. In EDM, a potential difference is applied between the tool and workpiece. Both the tool and the work material are to be conductors of electricity. The tool and the work material are immersed in a dielectric medium. EDM does not make direct contact between the electrode and the workpiece, eliminating mechanical stresses, chatter and vibration problems during machining [4]. Generally kerosene and deionised water is used as dielectric fluid in EDM. Tap water cannot be used as it ionizes too early and thus breakdown due to presence of salts as impurities occur. Dielectric medium is generally flushed around the spark zone. It is also applied through the tool to achieve efficient removal of molten material (figure 1). A gap is maintained between the tool and the workpiece. Depending upon the applied potential difference and the gap between the tool and workpiece, an electric field would be established. Generally the tool is connected to the negative terminal of the generator and the workpiece is connected to positive terminal.

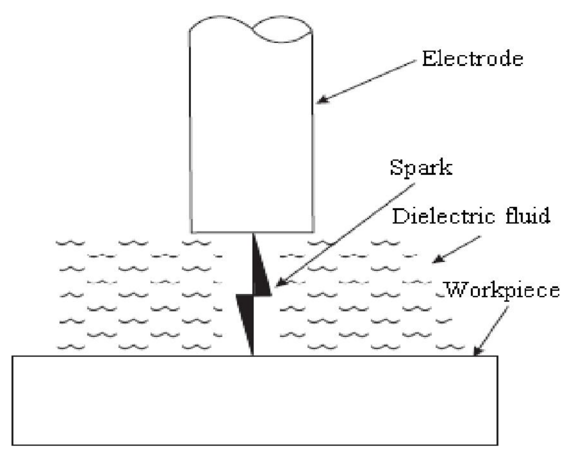


Figure 1. Electro discharge machining process [5].

Shape memory alloys (SMAs) are unique alloys in that they can remember an original shape after being deformed. The most common shape memory material is an alloy of nickel and titanium called Nitinol. This particular alloy has very good

electrical and mechanical properties, long fatigue life, and high corrosion resistance [6]. Numerous studies have been done for traditional and non-traditional machining of these alloys. Machining of TiNix smart alloy was studied by Chena et al. (2007). Their result shows that the machining of Ti35.5Ni49.5Zr15 and Ti50Ni49.5Cr0.5 alloys in EDM process depends on melting point and thermal conductivity. Surface roughness (Ra) in spark machining TiNiX alloys is obtained by
$Ra = \beta(I_p \times \tau_p)^{\alpha}$.

A small amount of $T_\theta \times K_T$, Ti50Ni49.5Cr0.5 alloy to Ti35.5Ni49.5Zr15 alloy will reduce the amount of Ra. Apart from for machining of TiNiX, the low discharge current and short pulse duration should be selected. A hard layer is formed on the outer of machined surface that is called the recast layer. Recast layer thickness depends on the amount of material removed and pulse duration [7]. Theisen and Schuermann examined the effect of EDM on the heat affected zone for NiTi alloy in pseudo-elastic condition. Material removal in EDM process depends on the electric discharge processes between the tool and the workpiece electrode. Materials are melting and vaporization by successive spark. The result of this is the different size and depth of the craters, which depends on discharge energy. Microstructure of this melting zone is characterized by hollows, cracks and precipitation. Open cracks have locally overlapping in the surface with each other. Structural analysis showed that the melting zone and freezing region should be taken to ensure that components are appropriate and it is possible with electrolytic polishing [8]. Chena and et al. in 2008, evaluated the electro-discharge machining (EDM) characteristics on the ternary NiAlFe alloy. Experimental results showed that the MRR of Ni60Al24.5Fe15.5 and Ti35.5Ni49.5Zr15 in the EDM process has inverse relationship with Alloy's melting point and thermal conductivity. Surface roughness of smart alloy (Ra) is obtained by empirical equation
$Ra = \lambda(I_p \times \tau_p)^{\beta}$.

Having a less value of $T_\theta \times K_T$, Ni60Al24.5Fe15.5 alloy caused increasing of Ra in depends on Ti35.5Ni49.5Zr15 alloy. Recast layer consists of Fe2O3, Al2O3, NiO and particles of copper tool that is solved on the dielectric. Thicknesses of the recast layer depend on pulse duration and amount of material, which remains, on the workpiece after MRR [9]. Considering the importance of titanium alloys in the medical, aerospace, automotive industry and etc [10]. EDM method is very important especially to produce accurate prototypes, micro-parts and all specific products. In this study, the effect of material removal rate and surface roughness of nickel-titanium is investigated and tools for highest material removal rate and low surface roughness is introduced.

2. Design of experiments

With design of experiments, main variables can be identified which affect on process quality. By using of experimental design, manageable input parameters can be changed and evaluate their effects on the output parameters. Generally, the aim of design of experiments is reducing of the less significance test and establishing a significant relationship between input and output parameters is the minimum tests. In This study Taguchi's method as one of the most powerful methods for analyzing design of experiments is used. For optimization of number of experiments and increase, the number of results to all surface, orthogonal array (L18 $2^1 \times 3^3$) is used [11]. In this investigation the number of examine and factor are 18 and 4 respectively. Factors or input parameters of the test are discharge current, pulse duration, pulse off time and voltage. Voltage Factor has 2 levels and other factors have a three-level. Input parameters and selected surfaces for each factors is shown in Table 1.

Table 1. The machining parameters of EDM in this study

Factors	Levels
Gap voltage (V)	30,50
Discharge current (A)	10,15,20
Pulse duration (µs)	35,50,100
Pause duration (µs)	30,70,200

For pulse current levels 15.10 and 20A and for pulse duration 50, 35 and 100 micro second levels, for pulse-off time factor 70, 30 and 200 micro second levels, 80 and 250V for gap voltage factor were selected. By changing any of these factors, their impact on output parameters such as material removal rate and surface roughness have been analyzed.

3- Experimental equipments

3-1- Electro discharge machine

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

3-2-Workpiece

Workpiece in this test is NiTi smart alloy. Samples are cutting and grinding by Wire EDM. Physical and mechanical properties of NiTi alloy is shown in Table 2.

3-3-Tool material

In this study copper and brass Tools is used. Tool diameter 10mm and length is 20mm. Table (3) and (4) shows the physical properties of copper and brass Tools [12].

Table 2. The physical and mechanical properties of Nitinol-60 [12]

Density	6.45 G/cc
Tensile strength, ultimate	754 - 960 Mpa
Tensile strength, yield	560 Mpa
Modulus of elasticity	75.0 Gpa
Shear modulus	28.8 Gpa
Electrical resistivity	0.0000820 Ohm-cm
Magnetic susceptibility	0.00000380
Thermal conductivity	10.0 W/m-k
Melting point	1240 -1310 °C
Solidus	1240 °C

Table 3. The physical properties of copper electrode [12]

Electrical resistivity	1.96 (μΩ/cm)
Electrical conductivity compared with silver	92 (%)
Thermal conductivity	268-389 (W/mK)
Melting point	1083 (C°)
Specific heat	0.092 (cal/g°C)
Specific gravity	8.9 (g/cm^3)

Table 4. The physical properties of brass electrode

Electrical resistivity	4.7 (μΩ/cm)
Electrical conductivity compared with silver	28 (%)
Thermal conductivity	26.0 - 159 (W/mK)
Melting point	1030 (C°)
Specific heat	0.380 (J/g°C)
Specific gravity	8.4 (g/cm^3)

3-4-Roughness tester

To measure the roughness of the workpiece surface roughness Mahr model M300-RO18 tester and to measure the weight of the workpiece before and after machining scale AND Model 300 with 0.0001gr precision is used.

4-Machining parameters

In this study effect of four variables consist of pulse duration, pulse off time, pulse current and voltage with copper and brass tools on material removal rate and surface roughness of NiTi alloy have been analyzed. Workpiece weight was measured before and after each machining step by scale with 0.0001 g precision. Equations 1 and 2 are used to calculate the material removal rate.

$$\text{VMR}\,(\text{mm}^3) = 1000\,\frac{\Delta\text{M (gr)}}{\rho\,(\text{gr/cm}^3)} \qquad (1)$$

$$\text{MRR}\,(\text{mm}^3/\text{min}) = \frac{\text{VMR (mm}^3)}{\text{T (min)}} \qquad (2)$$

In these equations, ρ is density of the workpiece, T is time machining, VMR volume of material removed from the workpiece and the MRR is material removal rate [13].

5-Assess the response of machining removal rate with copper and brass electrode

Effects of voltage, pulse current, pulse duration and pause duration on the MRR are shown in figures 2 to 5. In figure 2 MRR is shown for three current pulses consist of 10, 15 and 20A. According to figure, independently of the material tool, by increasing the pulse current, spark energy and resulting temperature of part surface increased and consequently melting and MRR increases. The factor of increasing the spark energy is rising of pulse current and the number of contact of ions in the specified duration [14]. By increasing the pulse current, energy and the number of ions that attack on surface of the work piece is increased consequently MRR is raised. According to figure 2 copper tools have the higher MRR than the brass tools.

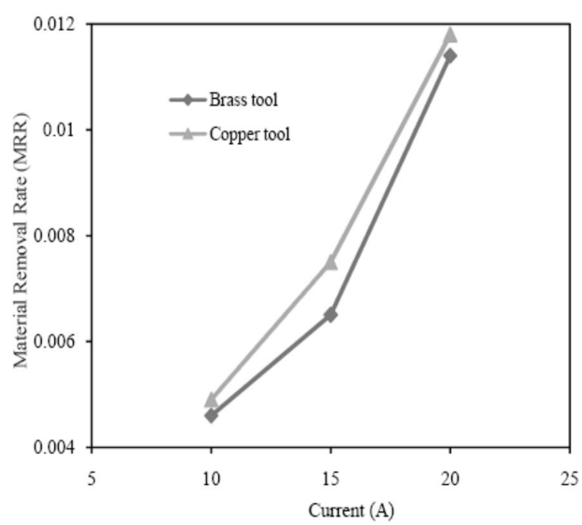
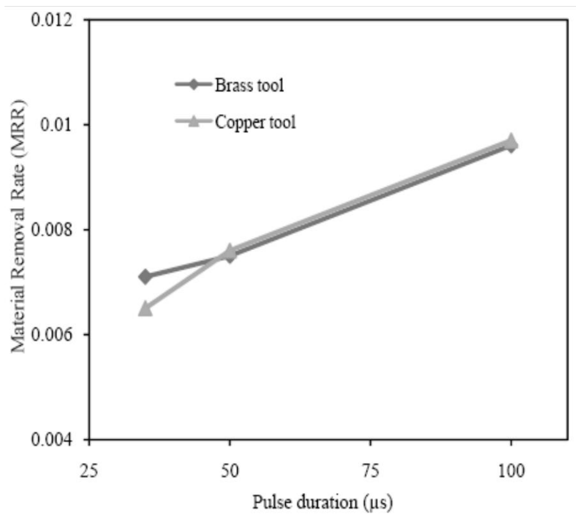


Figure 2. Relationship between MRR and discharge current

Figure 3 is shown MRR at the pulse duration of 35, 50 and 100μs. By increasing the pulse duration, independent of the tool material, increases MRR. By raising the pulse duration, the plasma channel is bigger and ions are more active therefore more discharge energy caused more melting and vaporization of the workpiece. Effects of pulse duration, on the MRR for copper and brass tools are almost same.



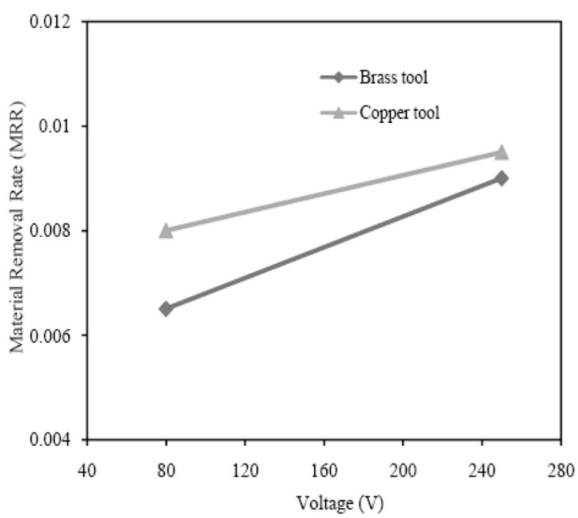
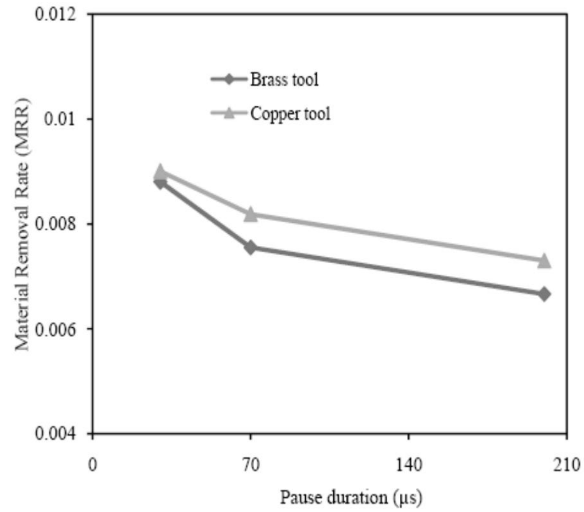
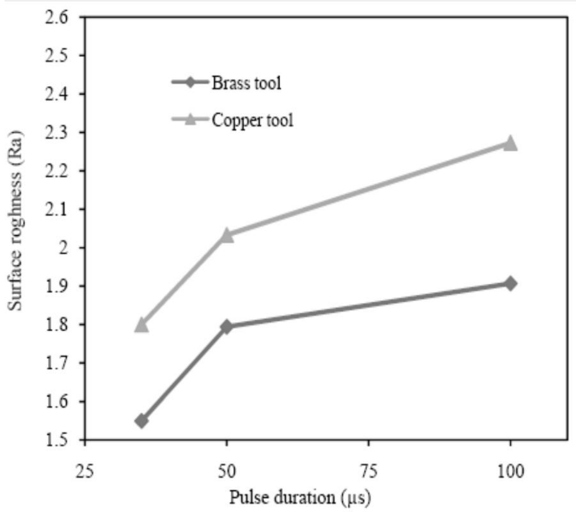


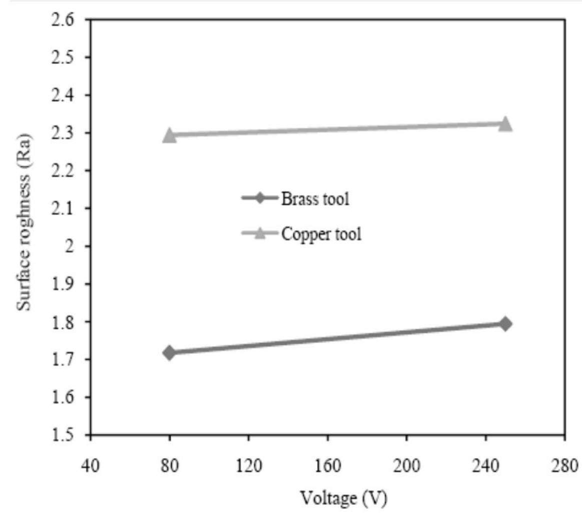
Figure 4. Relationship between MRR and gap voltage

Figure 5 is shown the effect of pause duration on the MRR. With increasing pause duration due to cooling of dielectric and thermodynamic issues, MRR decreases. In pause duration of 30µs we have maximum MRR and with increasing them MRR decreases. According to figure 5 at various pause duration, MRR of copper tool is higher than brass tool.



10 and 20A on the surface roughness of NiTi alloy. Current pulse has a significant effect on surface roughness and with increasing spark energy, MRR increased thus the surface roughness is increased. According to figure 7 at different pulse currents, surface roughness of copper tools is further than brass tools.





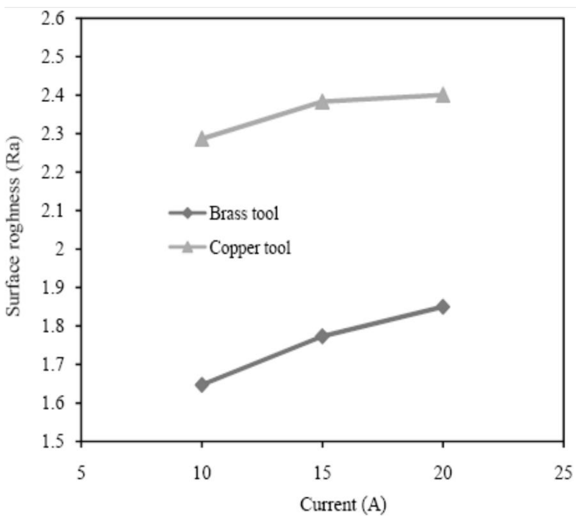


Figure 7. Relationship between surface roughness and discharge current

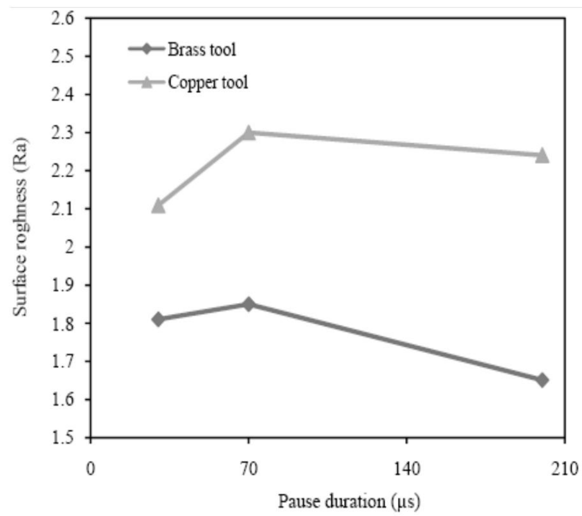


Figure 9. Relationship between surface roughness and pause duration

Figure 8 is shown the effect of voltage of 100, 80V on the surface roughness. With rising of voltage in this range, surface roughness is raised slightly. Spark voltage is a function of the workpiece, tool and dielectric materials.

Figure 9 shows the effect of pause duration on surface roughness of the NiTi alloy. Surface roughness increases with rising of pause duration to 70 micro-seconds and then after that decreases. According to figure 9, the increase of pause duration more than 70 microseconds, causes reducing the surface roughness and brass tool has less surface roughness than copper tool.

7-Conclusion

In this study, the effect of copper and brass tools, and input parameters such as current pulse, voltage gap, pulse duration and pause duration on output parameters such as surface roughness and material removal rate for smart NiTi alloy is investigated. Test result for NiTi smart alloy indicated that independent of tool material, the most important parameter on MRR is pulse current when it increasing, spark energy and MRR are increased. The next effective factor is the pulse duration which is increasing up to 100µs, MRR is increased. Copper tool has more MRR than brass tool by increasing the pulse current and pulse duration. MRR is reduced when pause duration is increasing in both tools. The test results shows independent of the type tool, the most important parameters on surface roughness are pulse current and pulse duration. By increasing current pulse and pulse duration, spark energy is increased and the surface roughness rises rapidly. Result shows that for machining of NiTi smart alloy, brass tool has less surface roughness than copper tool. Brass tool is recommended for high quality of surface in machining of NiTi smart alloy.

Acknowledgements:

This study is resulted from a research project in Islamic Azad University, Majlesi Branch. The author is thankful for supportive effort of this research benefactor.

Corresponding Author:
Esmaeil Abedi
Department of Mechanical Engineering, Majlesi Branch, Islamic Azad University, Isfahan, Iran
E-mail: e.abdi@iaumajlesi.ac.ir

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12/26/2012