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Influence of Machining Parameters on Electro Discharge Machining of NiTi Shape Memory Alloys

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NiTi is an alloy of nickel and titanium with important characteristics such as shape memory, superelasticity, high electrical resistance, high corrosion resistance, long fatigue life, and vibration absorption. The unique features of this alloy have made it useful in all types of industries. However due to these same characteristics, it is difficult to perform machining and forming operations on this alloy by traditional methods. One of the machining techniques suitable for NiTi alloy is electro discharge machining. The electro discharge machining process is one of the most practical nontraditional machining methods which are not influenced by the hardness and physical properties of the workpiece. This research intends to study the effects of electro discharge machining parameters such as voltage, discharge current, pulse on time and pulse off time on the rate of material removal, tool wear, relative electrode wear and surface roughness of NiTi alloy. For the design of experiments, the Taguchi's method for the design of experiments, L18 orthogonal array and the 'Minitab' software program have been used. The experiments indicate that the parameters of discharge current, voltage, and pulse on time have a direct impact on material removal rate (MRR), and with their increase, MRR increases as well. Tool wear rate (TWR) diminishes with the increase of pulse off time and discharge current. The analysis of results obtained for surface roughness indicates that pulse on time and off time have the highest impact on the surface roughness of NiTi alloy.

Keywords: NiTi; Electro discharge machining; Design of experiments; Tool wear rate; Surface roughness, Material removal rate

1. INTRODUCTION

Shape memory alloys (SMAs) are novel materials with the ability to return to a preset shape when heated. Shape-memory alloys are functional materials with a variety of applications. Their mechanical properties and their micro-structural changes at various strain rates and temperatures have been of considerable interest [1]. When an SMA is cold or below its transformation temperature, it has a very low yield strength and can be deformed quite easily into any new shape, which it will retain. However, when the material is heated above its transformation temperature, it undergoes a change in its crystalline structure, which causes it to return to its original shape. If the SMA encounters any resistance during this transformation, it can generate extremely large forces. This phenomenon provides a unique mechanism for remote actuation. Shape memory alloys, however, are not for all applications. One must take into account the forces, displacements, temperature conditions, and cycle rates required of a particular actuator. The most common shape memory material is an alloy of nickel and titanium called nitinol. Ni-Ti shape memory alloys belong to the group of materials known as smart functional materials. This particular alloy has very good electro and mechanical properties, long fatigue life, and high corrosion resistance [2]. Nickel-titanium alloys have the greatest recoverable strains among the commercially available shape memory alloys. Fully recoverable strains of 7% are easily achieved with these alloys [3].The thermal shape memory effect is an outstanding characteristic exhibited by NiTi alloys. The alloy recovers its programmed shape after being heated above a specific temperature, namely, the austenitic finish temperature (A_f), and also its superelastic (rubber-like) behavior. Both of these properties are based on thermo-elastic, reversible martensitic transformation [4]. The high-temperature austenite phase (with a body centered cubic structure) transforms martensitically upon cooling below an alloy-specific temperature into a distorted monoclinic martensite structure. NiTi shape memory alloys usually consist of binary alloys with Ni and Ti concentrations near the equiatomic composition. Other alloying elements like Fe, Cu and Nb may be added in order to influence transformation hysteresis behavior (shallower hysteresis for Fe and Cu, wider for Nb) as well as transformation temperature and mechanical properties, particularly fatigue properties. The microstructures of NiTi alloys are generally processed using complex [4-6]. Due to the high hardness of NiTi alloys, the traditional machining methods are not able to machine these alloys. One of the newer machining techniques that can handle NiTi alloys is the process of electro discharge machining (EDM). Electro Discharge Machining has been a well-known machining technique for more than fifty years. Nowadays, it is the most widely used non-traditional machining process, mainly to produce injection molds and dies, which are used for the mass production of common everyday objects. It can also be used to fabricate finished parts such as cutting tools and items with complex shapes. EDM is used in a large number of industrial applications such as the automotive industry, electronics, domestic appliances, machines, packaging, telecommunications, watches, aeronautic, toys, surgical instruments, etc.[7]. The EDM process has an advantage over the other machining techniques due to its ability to create complex and intricate parts with a high degree of accuracy. This process is able to machine hard materials, which would be difficult to machine by other machining processes. Another advantage of EDM is its ability to machine parts on an extremely small scale. EDM is commonly used in the fabrication of industrial tools, dies and molds, and the machining of heat treated ceramic materials such as tungsten carbides [8]. Furthermore, using this technique, complex cutting geometries, sharp angles and internal corners can be produced. Also, there is no mechanical stress on the machined piece, no rotation of the workpiece or tool is necessary, and the machines have a high autonomy. On the other hand, the disadvantages of EDM are the relatively low material removal rate, surface modification of the machined workpiece, and the limited size of workpiece and tool [7]. EDM is a controlled material removal technique, which uses high frequency electric sparks to erode the workpiece to the shape of the tool electrode. The machining tool (electrode) is made of electrically conductive material, usually copper or graphite [9]. In the EDM process, the electrode is brought closer to the work material until a small enough spark gap develops between them, through which the applied voltage can ionize the dielectric [10]. The EDM method uses the eroding effect of controlled electric spark discharges on the electrodes. Thus, it is a thermal erosion process. The sparks are created in a dielectric liquid, generally water or oil, between the workpiece and an electrode, which can be considered as the cutting tool. There is no mechanical contact between the electrodes during the whole process. Since material is removed by electro discharge, both electrode and workpiece have to be electrically conductive. Thus, the machining process works by successively removing small volumes of workpiece material, which melts or vaporizes during the electro discharge. Figure 1 demonstrates the erosion process due to a single EDM discharge. First, an ignition voltage, typically about 200 V, is applied between the electrodes. The breakdown of the dielectric is initiated by moving the electrode towards the workpiece. This increases the electric field in the gap, until it reaches the necessary value for breakdown. The location of breakdown is generally between the closest points of the electrode and workpiece, but it also depends on the particles present in the gap [9]. When breakdown occurs, voltage falls and a current abruptly appears. The presence of a current is possible at this stage, because the dielectric has been ionized and a plasma channel has been created between the electrodes. The discharge current is then maintained, assuring a continuous bombardment of ions and electrons on the electrodes. This causes the workpiece material (and also the electrode material) to heat up intensely, and rapidly creates a small pool of molten metal at the surface. A small quantity of metal can even be directly vaporized due to the heating [7]. Numerous research works have focused on the ways of optimizing the EDM performance and achieving high material removal rate (MRR), low tool wear rate (TWR) and satisfactory surface roughness (SR) [9].

So, the EDM method uses thermoelectric energy for material removal, and the mechanical properties of the workpiece have no effect on the efficiency of machining, and it can be used to machine very hard parts. This method has certain limitations such as low material removal rate and high tool wear and surface roughness, which many investigations have been conducted to come up with ways of improving these drawbacks.

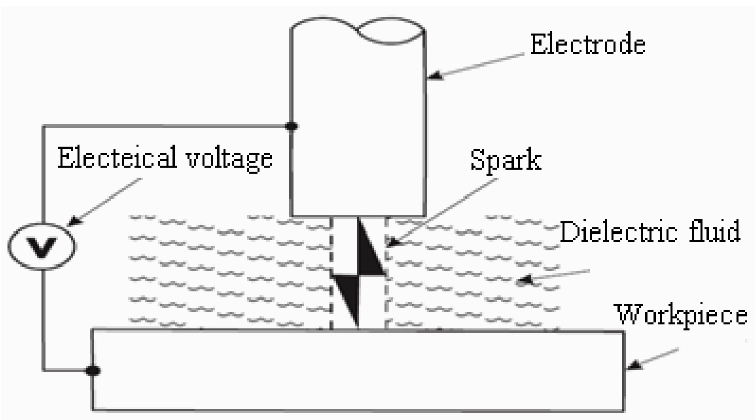

Figure 1. Basic components of EDM [13]

In 2004, Thisen et al. did some research on NiTi machining by the EDM method using tungsten-copper tools and found out that, by varying the voltage and current, the depth of cracks and surface roughness can be affected [11]. In 2007, Chen et al. investigated the effect of the EDM process on Ni-Al-Fr alloy, using kerosene dielectric, and concluded that material removal rate is inversely related to the melting point and thermal conductivity of the alloy. They investigated the effects of EDM on surface roughness and recast layers [12]. In this research, using copper tools and de-ionized water as the dielectric, the effect of the EDM's input parameters on output parameters has been studied for NiTi alloy.

2. TEST EQUIPMENTS

The workpiece used in the experiment is nickel-titanium alloy with weight percent 60% of nickel. The 10 x 60 x 50 mm workpiece has been cut out by the wire electro discharge machining, and grinded. The tool used in this research is made of copper, with dimensions of Φ10 x 20 mm, and it is attached to the anode. The physical and mechanical properties of the workpiece have been listed in Table 1. De-ionized water was selected as the dielectric used in this experiment in order to have the least effect on the recast layers of NiTi alloy [14]. To perform the experiments, an AZARAKHSH spark machine (model: 204H) was used. To measure the rate of material removal and tool wear, a 'AND' digital scale (model: GR-300) with an accuracy of ± 0.0001gr was used and to measure the surface roughness of the workpiece, a 'Mahr' roughness measuring instrument (model: M300-RD18) was employed.

Table 1. Mechanical and physical properties of Nitinol-60 [15]

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
Shear modulus	28.8 Gpa
Thermal conductivity	10.0 W/m-k
Melting point	1240 - 1310 °C
Nickel, Ni	60.0 %
Titanium, Ti	40.0 %

3. MODELING OF EXPERIMENTS

3.1. Input parameters

From among the input parameters of the electro discharge machining process, the discharge current, voltage, pulse on time and pulse off time, which have the highest impact on output parameters, were selected [16].

3.2. Output parameters

The output parameters investigated in this process include the material removal rate (MRR), surface roughness, tool wear rate (TWR) and relative electrode wear (REW).

4. DESIGN OF EXPERIMENTS

Through the design of experiments, the key variables that affect the qualitative characteristics of the process can be identified. By using this method, the controllable input factors can be systematically changed and their impacts on output parameters can be evaluated [17]. The experiments were designed as full factorial, and with mixed levels. Pulse on time and off time varied from 35-100 µs, and 30-200 µs, respectively. To optimize the number of experiments and extend the results to all the levels under investigation, the orthogonal array of L18 ($2^1 \times 3^3$) has been used. There are 18 experiments and 4 factors in this research. The input parameters in this investigation include the discharge current, voltage, pulse on time and pulse off time. The voltage factor has two levels and the rest of the factors have three levels each. The design of experiments has been shown in Table 2. To analyze the results, the 'Minitab 16' software program has been used.

Table 2. Design of experiments

Level	Design of Experiments		
Voltage overshoot (V)	80		250
Pulse on time (µs)	35	50	100
Pulse off time (µs)	30	70	200
Setting current (A)	10	15	20

5. MATERIAL REMOVAL AND TOOL WEAR RATES

In this research, the effects of input parameters (pulse on time, pulse off time, pulse current and voltage) on material removal rate and tool wear rate have been evaluated. The rates of material removal and tool wear were measured by weighting the workpiece and tool before and after the experiment with an accuracy of ± 0.0001gr. The relations corresponding to material removal rate and tool wear rate have been given in equations 1-4 [18].

$$VMR_p\,(mm^3) = 10000\,\frac{\Delta M(gr)}{\rho(gr/cm^3)} \tag{1}$$

$$MRR\,(mm^3/min) = \frac{VMR_p\,(mm^3)}{T(min)} \tag{2}$$

$$VMR_T\,(mm^3) = 10000\,\frac{\Delta M(gr)}{\rho(gr/cm^3)} \tag{3}$$

$$TWR\,(mm^3/min) = \frac{VMR_T\,(mm^3)}{T(min)} \tag{4}$$

ρ: Density of tool and workpiece
T: Machining duration
VMR_P: Volume of material removed from the workpiece
VMR_T: Volume of material removed from the tool
MRR: Material removal rate
TWR: Tool wear rate

6. ANALYSIS OF MATERIAL REMOVAL RATE

Figure 2 shows the impact of pulse current, pulse on time, pulse off time and voltage on material removal rate. With the increase of pulse current, the spark energy and consequently, the surface temperature of workpiece rises, and material melting and MRR increase rapidly. Spark energy intensifies with the increase of pulse current, pulse on time and voltage. The increase of pulse current increases the energy and number of positive ions attacking the surface of the workpiece and causes the temperature of the workpiece to rise, thereby melting and evaporating material from the workpiece surface and increasing the MRR. Also with the increase of pulse on time, the plasma channel becomes wider and positive ions become more active in attacking the cathode (workpiece). This causes more melting and evaporation of the workpiece, and leads to the increase of MRR. Figure 2 shows the impact of increasing the pulse on time on the material removal rate of NiTi alloy when using de-ionized water as the dielectric. Research works indicate that, with the increase of pulse on time, due to thermodynamic and heat transfer issues, the energy transferred to workpiece surface diminishes, and the material removal rate gradually loses its ascending trend and goes into a decline. In general, it can be said that the material removal rate has a direct relationship with the spark energy, and it increases with the increase of spark energy. Eq. 5 expresses the relationship between spark energy and pulse current and also pulse on time [18].

$$W_{av} = I_{sp} \times V_{sp}(T_{on} - T_d) \qquad (5)$$

The statistical analysis of the process using the design of experiments technique for the exact analysis of results indicates that pulse current and pulse on time are the most important parameters affecting the material removal rate of NiTi alloy. As has been shown in figure 2, with the increase of pulse current, material removal rate increases sharply; while with the increase of pulse on time, the increase of MRR has a milder increase. By increasing the pulse off time, the material removal rate of NiTi alloy using copper tools diminishes. The increase of pulse off time causes the plasma channel to become smaller, which reduces the attack of positive ions on the workpiece surface and lowers the MRR. Comparison of results of material removal rate with methods that use kerosene as a dielectric shows that material removal rate decreases considering that the sparks are less stable [19, 20, 21].

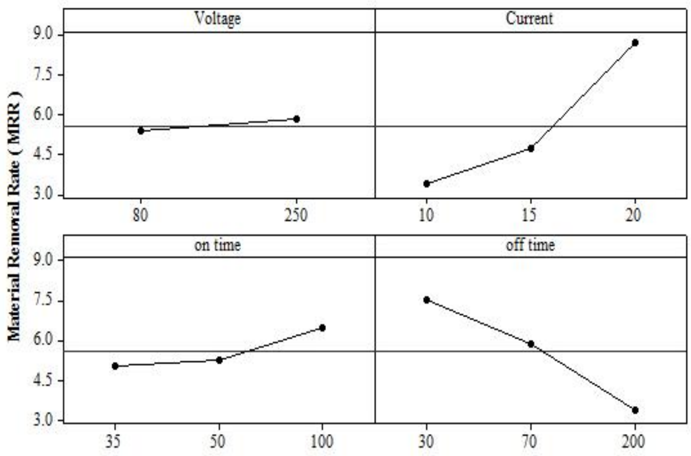

Figure 2. Impact of input parameters of the process on material removal rate of NiTi SMA

7. ANALYSIS OF TOOL WEAR RATE (TWR)

Figure 3 illustrates the impact of pulse current, pulse on time, pulse off time and voltage on the tool wear rate. With the increase of these parameters, the energy of each pulse increases, and since one end of the pulse is on the tool and the other end is on the workpiece, this increases the amount of wear in the tool. Tool wear depends to a large extent on tool material and pulse energy; and for a specific tool, the amount of tool wear increases with the increase of pulse energy. The analysis of figure 3 indicates that increasing the pulse on time beyond 50μs leads to the reduction of tool wear. These changes occur due to the fact that at the onset of electro discharge, the diameter of plasma channel is small, and lightweight electrons move towards the anode (positive pole) under the influence of electric field and cause the melting and evaporation of the tool. As time passes, the plasma channel diameter increases and more positive ions move towards the cathode (negative pole) and thus, more material is removed from the workpiece. The increase of pulse current and pulse off time during the machining of NiTi SMA with copper tools and de-ionized water dielectric leads to the reduction of tool wear, and the increase of voltage results in the increase of tool wear (figure 3).

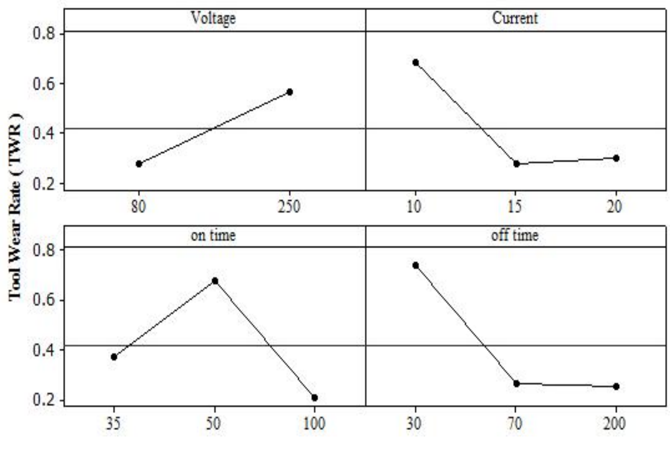

Figure 3. Impact of input parameters of the process on tool wear rate of copper tools

Tool wear results with de-ionized water in comparison with kerosene shows that tool wear is reduced and machining accuracy is improved considering that the de-ionized water is less stable and breaks down faster [22, 23].

8. ANALYSIS OF ELECTRODE WEAR RATE (EWR)

Figure 4 shows the impacts of pulse current, voltage, pulse on time and pulse off time on electrode wear rate. With the increase of pulse, current, electrode wear rate diminishes in the machining of NiTi alloy using de-ionized water. The reason is that by increasing the pulse current, the spark energy and consequently, the surface temperature of the workpiece increases, which sharply reduces the relative electrode wear and increases the workpiece wear. The increase of spark energy with the rise in pulse current causes more electrons to impact the tool; and as time passes and plasma channel diameter increases, more protons hit the workpiece. With the increase of pulse on time in the machining of NiTi alloy with copper tools up to 50µs, the relative electrode wear increases, and a further increase of pulse on time beyond the 50µs reduces the EWR. The increase of pulse off time up to 70µs leads to the reduction of relative electrode wear, and a further increase of pulse off time between two pulses beyond the 70µs point causes the EWR to diminish. Compare the results with methods that use kerosene as dielectric indicates that due to reduction in MRR and TWR, electrode wear rate decreases by using of de-ionized water [24, 25].

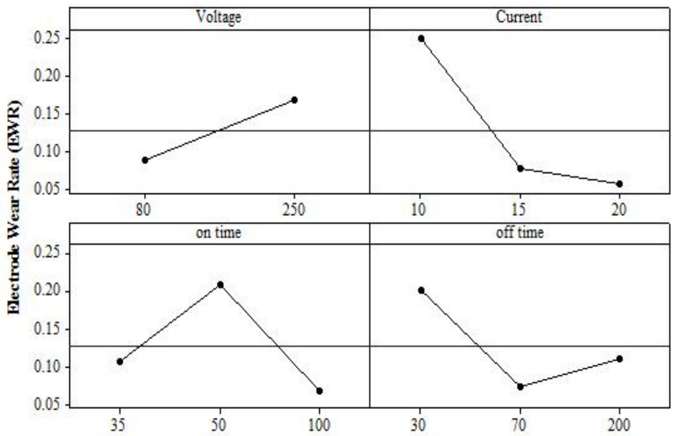

Figure 4. Electrode wear rate (%)

9. ANALYSIS OF SURFACE ROUGHNESS

The effect of input parameter of pulse current, pulse on time and pulse off time on surface roughness has been demonstrated in figure 5. Surface roughness increases with the increase of pulse current. The increase of surface roughness is due to the increase of spark energy, which causes the surface pits resulting from the removal of material to enlarge. With the increase of pulse on time in the machining of NiTi alloy using copper tools up to 70µs, surface roughness diminishes; and a further increase of pulse on time beyond 70µs results in the increase of surface roughness. Voltage has less of an effect on surface roughness. In the machining of NiTi alloy using de-ionized water as the dielectric, the least amount of surface roughness is obtained with the least value of pulse current and the pulse on time of 50μs. Test results of surface roughness with copper tool and de-ionized water dielectric in compare with brass tool and copper with kerosene dielectric shows that the use of de-ionized water reduces the surface roughness [26].

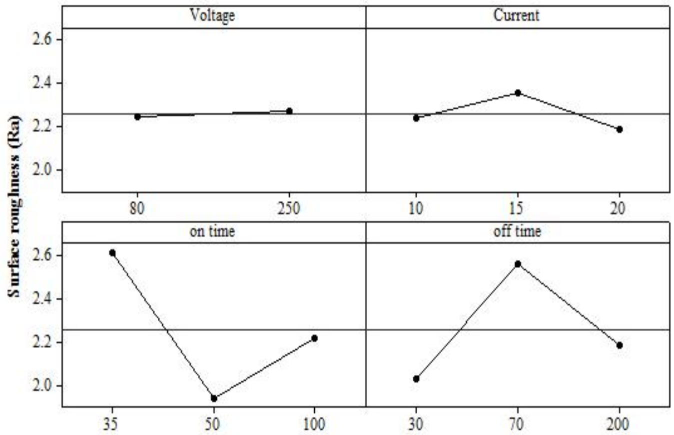

Figure 5. Impact of input parameters of the process on surface roughness

10. CONCLUSION

In this research, the impacts of input parameters of electro discharge machining process including the voltage, pulse current, pulse on time and pulse off time on the output parameters of material removal rate, tool wear rate, relative electrode wear and surface roughness were investigated for the machining of NiTi smart alloy using copper tools and de-ionized water as the dielectric. In performing the experiments, the technique of design of experiments was used in order to obtain the process responses. It was demonstrated in this research that the most significant and effective factors in the material removal rate of NiTi alloy machined by copper tools are the pulse current and pulse on time, whose increase intensifies the spark energy and increases the material removal rate. With the increase of pulse current in NiTi alloy, surface roughness increases. With the increase of pulse on time up to 50μs, tool wear rate increases and beyond that point, tool wear diminishes. The increase of pulse off time causes the reduction of tool wear and MRR. To obtain the least amount of surface roughness, the least values of pulse current and pulse on time should be chosen and the off time between two pulses should be increased. In the machining of NiTi alloy using copper tools and de-ionized water, the highest values of pulse current and pulse on time were selected to achieve the maximum material removal rate. The increase of voltage leads to the increase of MRR and TWR and the enlargement of surface pits, which reduces the quality of the machined surface. To increase the efficiency of the EDM process, material removal rate should be high. But with the increase of MRR, tool wear rate also increases; and according to the obtained results, the quality of the machined surface will diminish as well. Therefore, it would be necessary to carry out the process in several stages. First, by increasing the current and pulse on time, MRR is increased until the workpiece gets closer to its final shape and then in the final and finishing stage, the workpiece is machined with other tools and by applying a lower pulse current and pulse on time, so that the TWR is reduced and a higher quality surface finish is achieved by the EDM process.

References

1. S. Nemat-Nasser, J.Y. Choi, W.G. Guo, J.B. Isaacs, *Mechanics of Materials*. 37 (2005) 287.
2. S.R. Areef, *Engineering and Technology Journal*. 28 (2010) 992.
3. C. Darjan, J. Dolinsek, *Shape Memory Alloys*, University of Ljubljana, (2007) 1.
4. J. R. Davis, *Properties and Selection Nonferrous Alloy and Special Purpose Materials*, ASM International, (1990) 897.
5. GF. Andreasen, JL. Fahl, *Alloys Shape Memory*, Wiley, New York (1987) 15.
6. W. Buehler, F. Wang, *Ocean Engineering*. 1 (1968) 105.
7. A. Descoeudres, *Characterization of Electrical Discharge Machining Plasmas*, Ecole Polytechnique Federale De Lausanne, (2006).
8. S. Shahril, M.Yunus, *Effects of Flushing on Electro-Discharge Machined Surface*, University Malaysia Pahang, (2008).
9. G.K.M. Rao, S. Satyanarayana, M. Praveen, *Proceedings of the World Congress on Engineering*, London, July 2 - 4, (2008) 1.
10. A. Pandey, S. Singh, *Journal of Engineering Science and Technology*. 2 (2010) 2172.
11. W. Theisen, A. Schuermann, *Materials Science and Engineering A*. 378 (2004) 200.
12. S.L. Chen, S.F. Hsieh, H.C. Lin, M.H. Lin, J.S. Huang, *Materials Science and Engineering A*. 445-446 (2007) 486.
13. E.C. Jameson, *Electro Discharge Machining*, Society of Manufacturing Engineers (SME), 2001.
14. H.C. Lin, K.M. Lin, Y.S. Chen, C.L. Chu, *Journal of Materials Processing Technology*. 161 (2005) 435.
15. http://www.Matweb.com.
16. S.H. Lee, X.P. Li, *Journal Material Process Technology*. 115 (2001) 344.
17. D.C. Montgomery, *Design and Analysis of Experiments*, Wiley, New York (2008).
18. J.A. Geough, *Advanced Method of Machining*, Springer, New York (1988).
19. R. Atefi, A. Razmavar, F. Teimoori, *Journal of Basic and Applied Scientific Research*. 2 (2012) 2311.
20. K. Bonny, P. De Baets, J. Vleugels, O. Van der Biest, B. Lauwers, *Journal of Manufacturing Research*. 4 (2009) 375.
21. H.R. Sabouni, S. Daneshmand, *Life Science Journal*. 9 (2012) 504.
22. M.K.A.B. Mohd Idris, *Effects of Machining Characteristics on Electric Discharge Machine Using Different Electrode Materials*, University Malaysia Pahang, (2008).
23. E.A.A. Khudair, M.M. Khuder, *Effect of Current on Electrical Discharge Machining*, University of Technology Production and Metallurgy Iraq, (2011).
24. S. Daneshmand, E. Farahmand Kahrizi, M. Mortazavi Ghahi, *Australian Journal of Basic and Applied Sciences*. 6 (2012) 218.
25. P. Janmanee, K. Jamkamon, A. Muttamara, *European Journal of Scientific Research*. 76 (2012) 133.
26. H. Singh, A. Singh, *Journal of Modern Engineering Research*. 2 (2012) 4478.