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Wire electro-discharge machining of titanium alloy

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Abstract

This paper presents an experimental investigation of wire electro-discharge machining (WEDM) of titanium alloy. The objective is to investigate the effect of seven process parameters including pulse width, servo reference voltage, pulse current, and wire tension on process performance parameters (such as cutting speed, wire rupture and surface integrity). A Taguchi L18 design of experiment (DOE) has been applied. All experiments have been conducted using Charmilles WEDM. It was also found that the cutting speed increases with peak current and pulse interval. Surface roughness was found to increase with pulse width and decrease with pulse interval. The *Analysis of Variance (ANOVA)* also indicated that voltage, injection pressure, wire feed rate and wire tension have non-significant effect on the cutting speed. Scanning Electron Microscopic (SEM) examination of machined surfaces was performed to understand the effect of different wires on work piece material surface characteristics. A brief review of WEDM of titanium alloy is also included in the paper.

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1. Introduction

Titanium is a metal with excellent corrosion resistance, fatigue resistance, a high strength-to-weight ratio that is maintained at elevated temperature. Titanium and its alloys are attractive and important materials in modern industry due to their unique properties that are mentioned [1,2]. Titanium is a very strong and light metal. This property causes that titanium has the highest strength-to-weight ratio in comparison the other metal that are studied to medical use. Titanium is also incredibly durable and long-lasting. When titanium cages, rods, plates and pins are inserted into the body, they can last for upwards of 20 years. Titanium non-ferromagnetic property is another benefit, which allows patients with titanium implants to be safely examined with MRIs and NMRI [3,4,5]. Titanium and its alloys are used in many different industries such as biomedical

applications, automobile, aerospace, chemical field, electronic, gas and food industry [6]. In recent decades, titanium is applied widely in biomedical and medical field because it is absolutely a proper joint with bone and other body tissue, immune from corrosion, strong, flexible and compatible with bone growth. Titanium is used in different medical applications such as dental implants, hip and knee replacement surgeries, external prostheses and surgical instruments [4,7,8]. On the other hand, there is some limitation for titanium use because of its initial high cost, availability, inherent properties and manufacturability [9].

Machining titanium and its alloys by conventional machining methods has some difficulties such as high cutting temperature and high tool wear ratio. Thus, titanium and its alloys are classified as “difficult-to-machine” materials. Therefore, unconventional machining processes are introduced for machining titanium and its alloys [2,6].

1.1. Literature Review

Research and development on titanium's medical application is concentrated on studying titanium properties in order to enhance its mechanical properties, prevent corrosion and surface treatment that improve biocompatibility.

All research and developments about the titanium properties as biomedical and health care application in detail were reviewed [10]. The appropriate microstructure of titanium with optimum mechanical properties such as wear resistance and mechanical and biological compatibility was discussed [11]. The corrosion and fatigue behavior of titanium used in implant were reviewed with respect of the effect of different environmental condition [12, 13]. Machining titanium in the minimum time and with maximum precision is an important issue in all application fields of titanium especially biomedical. Wire EDM uses electro-thermal mechanisms to cut electrically conductive materials. Several researchers have attempted to improve the performance of WEDM of titanium as noted below.

A new methodology was employed to find the influences of process parameters on characteristics of titanium surface machined by WEDM process [2]. A strategy and advanced optimization were proposed to determine the optimal combination of control parameters of WEDM for obtaining higher performance in machining titanium aluminide alloy by Artificial Neural Network (ANN)[14]. A semi-empirical model was developed based on the properties of machined materials and WEDM parameters to find their influence on the volumetric efficiency of cutting [15]. The optimal parameters for surface finish in WEDM of titanium alloys were determined by employing Taguchi methodology [16]. The influence of WEDM on the corrosion rate and depth of damaged layer in the surface of pure titanium grade 4 and Ti-6Al-4V (grade 5) was investigated[17]. [9,18] conducted experiments on WEDM for titanium in order to determine how the process parameters change machining performances such as surface roughness, cutting rate and gap current.

The temperature increases during machining of titanium because of low thermal conductivity and high chemical reactivity of titanium. Thus, the probability of wire breakage increases during machining of titanium when the cutting temperature at wire/work piece enhances. The wire breakage during machining materials has an important and direct effect on WEDM process performance.

A thermal model was developed in order to investigate the influence of physical process parameters on wire rupture [19]. A WEDM sparking frequency monitoring system was introduced in order to predict the wire breakage in WEDM process [20]. The influence of the wire material properties on WEDM machinability was

reported [21]. The wire failure in WEDM process was investigated [22]. Two new wires that are called High-Falcon (HIF) and High-Eagle (HIE) were introduced and their properties and difference were analyzed [23]. The development of new wire that is called composite wires is studied [24]. The recent development in wire electrode types and their characteristics during WEDM process were reviewed [25]. The wire breakage reasons and its effect on machining performance in WEDM process were identified and explained [26]. The effect of coated wire on productivity and surface integrity of machined materials by WEDM was evaluated. They focused on aerospace materials [27].

The purpose of this study is to analyze a wire electrical discharge machining (WEDM) performance parameters (cutting speed, surface roughness and wire rupture) of Ti6Al4V in relation to process parameters and different wire electrode materials. Therefore, Optimization of WEDM process, determination of optimal values of process parameters and SEM examination are performed.

2. Experiment

The Charmilles Model 2020 Wire EDM (WEDM) was used to carry out the experiments. The Ti6Al4V has been applied as work piece material for the present experiments. The chemical composition of Ti6Al4V is given in Table 1. The shape was machined by WEDM with 5 mm × 10 mm × 15 mm size. Two types of wire electrode were used namely high-speed brass wire and zinc-coated brass wire. Table 2 illustrates the properties of wire electrodes. De-ionized water was selected as the dielectric for experiments, as that is the standard for Wire EDM.

Table 1
Chemical composition of Ti6Al4V (wt %)

C	Fe	Al	O	N	V	H	Ti
0-0.08	0.22	6.08	0-0.2	0.05	4.02	0-0.15	Balance

Table 2
Wire electrode materials properties

Wire Name	High-Speed Brass	Zinc-Coated Brass
Material	High Purity Brass Special Composition	CuZnBrass, 63/37 Core Composition with Zinc Coating
Tensile Strength	142,000 PSI	130,000 PSI
Wire Diameter	0.25 mm	0.25 mm

In this work, the effect of seven control factors was studied. These parameters with their levels are listed in Table 3. Apart from parameters mentioned

in Table 3, some machining parameters were kept constant as a fixed value during experiments (Table 4) in order to optimize the process. The machining parameters were chosen based on review of literature and experience.

The S/N ratio and average value of the response characteristics for each variable at different levels were calculated from experimental data. To measure the material removal rate, a straight cut is made into the work piece and the steady cutting speed value was read off the graphical display. To measure the surface roughness of the cut samples, Surfcom 130/480A was applied

Table 3
Machining conditions in WEDM

Symbols	Control factors	Units	Level		
			L1	L2	L3
A	Pulsewidth	μs	0.3	0.5	0.7
B	Timebetweenwopulses	μs	14	18	22
Aj	Servo referencemeanvoltage	V	30	40	50
IAL	Striking Pulse Current	A	6	9	12
INJ	Injection pressure	bars	5	7	9
Wb	WiremechanicalTension	daN(kg)	0.7	0.9	1.1
V	Voltage		L1	L2	
			-80	-100	

Table 4
Fixed machining parameters

Symbol	Machining parameters	Value
TAC	Short pulse time	0.3
S	Maximum rate of linear feed for machining	3
Ws	Wire feed speed (m/min)	15
M	Machining mode	1
FF		100

Scanning Electron Microscopy (SEM) views of the WEDMed surfaces were taken by Quanta 200 FEG Scanning Electron Microscope.

3. Results and Discussion

The experimental results are collected for cutting speed and surface roughness. 18 experiments were conducted using Taguchi (L_{18}) experimental design methodology and there are two replicates for each experiment to obtain S/N values. In the present study all the designs, plots and analysis have been carried out using Minitab statistical software. Larger cutting speed amount and lower amount of surface roughness show the high productivity of Wire EDM. Therefore, large the better and small the better are applied to calculate the S/N ratio of cutting speed and surface roughness respectively.

1. Larger the Better:

$$(S/N)_{HB} = -10\log (MSD_{HB})$$

Where:

$$MSD_{HB} = 1/R \sum_{j=1}^R (1/y_j^2)$$

2. Smaller the Better:

$$(S/N)_{LB} = -10\log (MSD_{LB})$$

Where:

$$MSD_{LB} = 1/R \sum_{j=1}^R (y_j^2)$$

Experiments were conducted using L_{18} OA to find the effect of process parameters on the cutting rate and surface roughness. The rate of cutting speed for titanium work piece and tool materials were collected in same experimental conditions.

First of all ANOVA table is carried out for all process parameters to determine the significant ones. Then, response curves were plotted in order to detect the influence of significant parameters on response.

3.1 Effect on Cutting Speed

The analysis of ANOVA table indicates that machining voltage, injection pressure, wire feed rate, servo reference voltage and wire mechanical tension are non-significant process parameters for cutting speed because their P-value is more than 0.05. Therefore, Pulse width, peak current and time between two pulses significantly affect the cutting speed values in WEDM of titanium by both wire types.

Figure 1 is plotted based on the results are achieved from machining of titanium by zinc-coated brass wire. The Figure 1 shows that when pulse width and peak current increase the cutting speed increases, and cutting rate decreases with increase in time between two pulses. This is because of increase in discharge energy and enhancement in pulse width and peak current that lead to a faster cutting rate. The number of discharges within a given period becomes less because the time between two pulses increase which leads to a lower cutting rate.

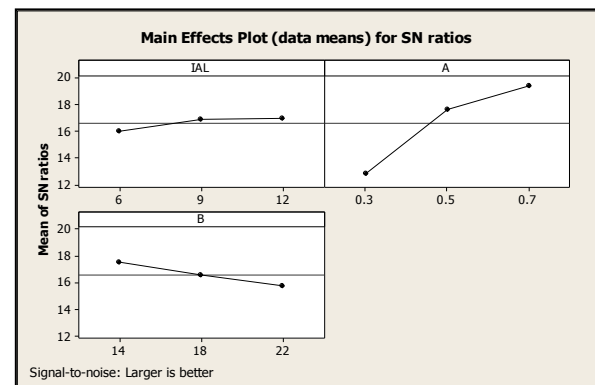


Figure 1 Effect of Significant Parameters on Cutting Speed (zinc-coated wire)

Figure 2 shows the results achieved from machining of titanium by high-speed brass wire. As you can see, the trend and effect of peak current, pulse width and time between two pulses in Figure 1 and 2 are same as each other.

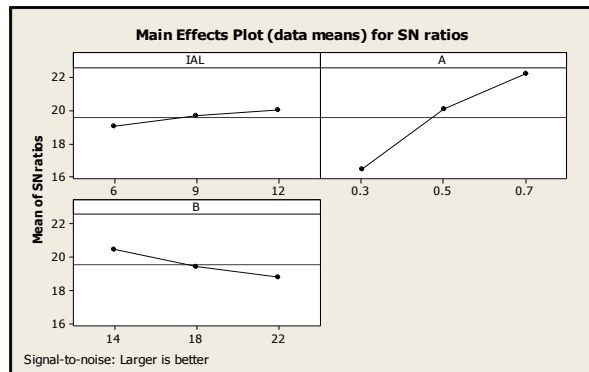


Figure 2 Effect of Significant Parameters on Cutting Speed (high-speed brass wire)

The optimal values for both wire material types are the third level of peak current (IAL_3), first level of time between two pulses (B_1), and third level of pulse width (A_3) provide maximum value of cutting speed.

The range of cutting speed with zinc coated wire is higher than high speed brass wire. In fact, the addition of zinc to brass wire leads to reduction in wire melting point. The low melting temperature of wire improves the spark formation and decrease dielectric ionization time. Thus, the cutting rate increases.

3.2 Effect on Surface Roughness

ANOVA table results revealed that in WEDM of titanium with both wire types voltage, time between two pulses, servo mean references and injection pressure do not have any influence on surface roughness. Other parameters such as pulse width, wire tension and peak current are the significant parameters for surface roughness.

The following Figures 3 and 4 plotted for machining of titanium by zinc-coated brass wire and high-speed brass wire respectively. It is observed from Figure 3 and 4 surface roughness value increases when pulse width and peak current increase. The discharge energy increases with the pulse on time and peak current and larger discharge energy produces a larger crater, causing a larger surface roughness value on the work piece. On the other hand, increase in wire tension causes reduction in surface roughness. Therefore, surface roughness quality of the machined part improves due to increase of wire tension because its vibration reduces.

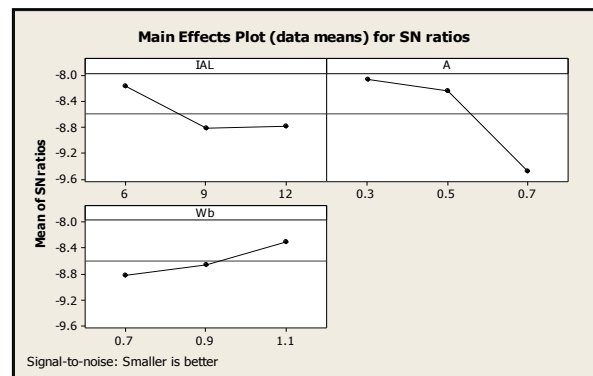


Figure 3 Effect of Significant Parameters on Surface Roughness (zinc-coated wire)

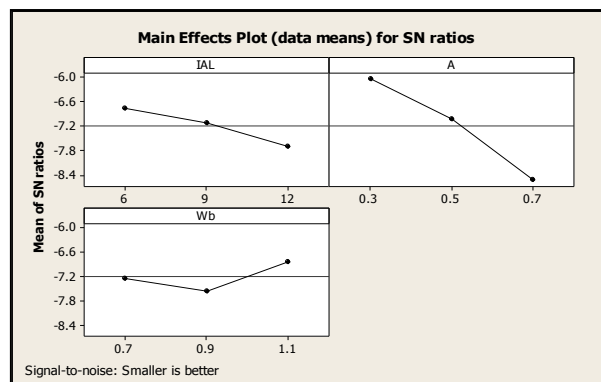


Figure 4 Effect of Significant Parameters on Surface Roughness (high-speed brass wire)

No difference between the optimal values obtained for machining of titanium with zinc-coated brass wire and high-speed brass wire was found. Analysis of the results of S/N ratio and raw data leads to conclusion that factors pulse width at first level (A_1), peak current at first level (IAL_3) and wire tension at third level (Wb_3) can be set for minimization of surface roughness.

The zinc-coated brass wire can produce smoother surface in comparison with high speed brass. The existence of zinc in coated brass wire provides higher tensile strength for wire. The wire with high tensile strength is a good heat resistance in high temperature and maintains straight under vibration and tension. Also, the uniform zinc layer on coated wire provides good discharge characteristics. A finer discharge can be created with good discharge characteristics and higher tensile strength. As a result, the quality of work piece surface will improve.

3.3 Effect on Wire Rupture

As mentioned in literature review sections there are some reasons and phenomenon that cause wire rupture during machining. Based on the experiments in this research, pulse width (A) and time between two pulses (B) are the most crucial machining parameters that affect wire breakage. The wire

rupture probability enhances when pulse-width increases and time between two pulses decreases simultaneously. The number of discharges within a given period of time becomes more when time between two pulses (B) is shorter and large pulse duration or width (A) leads to higher electrical discharging energy generates more heat energy. Therefore, the excessive thermal load, with increased discharge energy, results in wire breakage.

On the other hand, wire mechanical tension (Wb) and injection pressure (INJ) are effective parameters in reduction of wire breakage when pulse width and time between two pulses are small and large enough respectively. Wire tension reduction and increase in injection pressure can decrease wire rupture possibility while machining.

Experiments disclosed the frequency of wire rupture in machining of Titanium is more than machining of D2 Steel. Also, wire breakage phenomenon during titanium machining is more sensitive to changing of electrical parameters such as time between two pulses, pulse duration, wire tension and injection pressure. The high temperature generated while machining of Titanium due to the low thermal conductivity and high chemical reactivity of titanium alloys result in more wire breakage.

High speed brass wire resistance against wire rupture in tough conditions, high pulse width and low time between two pulses, is much more than zinc coated wire for both work pieces materials. However, coated layer has to decrease the risk of rupturing wires because it protects the core of the wire from thermal shock of electrical discharge and increase wire mechanical tensile strength. In fact, the tensile strength of zinc coated wire is more than normal brass wire but in this case the tensile strength (130,000 PSI) of zinc coated wire is less than the high speed brass wire tensile strength (142,000 + PSI).

3.4 Results of SEM Micrographs of WEDM Surface

Scanning Electron Microscopy (SEM) views of the WEDMed surfaces were taken in order to compare the effects of different wire types on machining of titanium materials by analyzing surface integrity and characteristics.

Figure 5 shows a comparison between the surface of titanium machined in same conditions and processing parameters value by high speed brass wire and zinc coated brass wire. It is evident that the specimen is produced with uncoated wire in Figures c and d have more melted drops, globules of debris, craters and cracks. As it can be seen in Figures a and b, due to low melting temperature and high heat conductivity the zinc coated wire produces better surface quality for titanium.

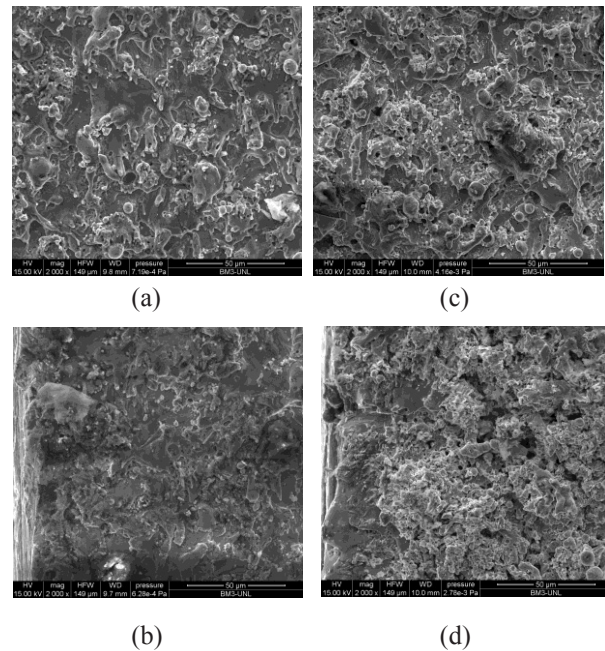


Figure 5
SEM Micrograph of Titanium

4. Summery

In this study, the influence of zinc-coated brass wire on the performance of WEDM is compared with high-speed brass. Also, the effect of process parameters on the process performance was determined by performing experiments under different machining conditions. Based on the experimental results and analysis, the following conclusions can be drawn:

- Experiments results of WEDM of titanium indicate peak current and pulse width have significant effect on cutting speed and surface roughness. Pulse width and peak current have direct relation with cutting speed but there is an inverse relation between surface roughness and them. Apart from these parameters, cutting speed of machining decreases with increasing time between two pulses and when wire tension increases surface roughness also increases.
- The wire breakage in machining of titanium is sensitive to electrical process parameters such as time between two pulses, pulse width, wire tension and injection pressure.
- Compared with high-speed brass wire, zinc-coated brass wire results in higher cutting speed and smoother surface finish. Also, SEM photographs proved that uncoated wire produces a surface finish with more cracks, craters and melted drops. However, High speed brass wire resistance against wire rupture in tough conditions, high pulse width and low time between two pulses, is much more than zinc coated wire since tensile strength (130,000 PSI) of zinc coated wire is less than the

high speed brass wire tensile strength (142,000 + PSI).

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