Investigation into energy interaction behavior of nitinol SMA during WECM

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Shape Memory Alloy,
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ABSTRACT

Wire Electrochemical Machining (WECM) combines the advantages of electrochemical machining working principle with the kinematic of wire EDM which is properly applied for fabrication of micro-features. WECM utilizes the advantages of these processes to enhance machining quality. Exceptional features of shape memory alloys (SMA) make them encouraging for widely advanced industrial applications. These difficult-to-cut materials micromachining without affecting original properties plays crucial role. Through this paper, an attempt has been made for the improvement of WECM during micromachining of nitinol SMA and explains the fundamentals of WECM process. This paper discusses various elements of developed WECM system. The paper also includes some experimental results of micro-slit machining by utilizing developed WECM setup and energy interaction behavior during fabrication of microslits of nitinol SMA. The homogeneous microslit with average slit width 111 µm with 1.68 µm standard deviation has been fabricated at 5V pulse voltage and 1.4 µm/s wire feed rate.

1. Introduction

In today's scenario of ultra-precise, advanced equipment, manufacturing industries have no option but to opt for automation and miniaturization to produce sophisticated products. WECM is one of the most appealing and promising technology in the area of micro-part manufacturing where machining is carried out with an anodic dissolution process without HAZ and change in properties of the material. This technique can be employed for the fabrication of complex 3D micro-features of any electrically conductive material. Shape memory alloy i.e. nitinol is very difficult-to-cut material as its super-elastic properties. Reviews of different research activities conducted in the area of WECM in the past as well as the basic nitinol micro-machining processes involved are presented herewith. Bisaria & Shandilya (2018) used the EDM process for nitinol SMA by taking into account different input process variables parameters during machining. Debnath et al. (2017) in-situ fabricated wire electrode and investigated the effect of high frequency and duty ratio during WECM. Sharma et al. (2018) observed that traditional machining of nitinol decreases its properties and releases Ni+ ions. Sharma et al. (2020) reviewed the entire WECM process and its application in fabricating complex micro-features using different work materials. Vakharia et al. (2022) found that the surge in T_{off} decreases the discharge and thermal energy obtaining a tiny crater with better smooth surface after machining. Wang et al. (2020) revealed that the requirement for shape memory alloy was improved fast subsequent to realizing their capability to preserve original shape after the deformation stage at plasticity. Woo et al. (2019) revealed that the thermal deformation and residual stresses problems of shape memory alloys can be solved using electrochemical machining processes.

This paper, therefore, emphasizes the improvement of WECM during micromachining of nitinol shape memory alloy by investigating input energy interaction behavior and its effects during the fabrication of micro slits in different zones through redox reaction considering different levels of pulse voltages and wire feed rate.

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2. Experimental Setup

The concept of applying WECM for the micromachining of shape memory alloy has been proposed. WECM machining kinematics is different than other ECM processes due to the side cross-section of the wire electrode. Combining hardware and software systems was a tedious task. In the present research work, an effort has been made to design and develop the full-fledged WECM system which will be less expensive, versatile, and economically viable in comparison with prevailing other non-conventional machining methods for the successful adaptability of this system in the various manufacturing industries. The actual developed WECM experimental set up as shown in fig.1 mainly consists of a mechanical machining unit, fluid flow circulation unit, and power supply units.

(i) Mechanical machining unit

The mechanical machining unit has been equipped with various functional elements such as a tool holding and feeding unit and a workpiece mounting unit. A tool-holding device fabricated from acrylic material is developed and attached to the Z-axis of the stage. The XYZ translation stage on which the tool is mounted has a resolution of 0.1 µm with 100mm total travel length for each axis. The workpiece mounting unit is also fabricated from acrylic material since it possesses resistance to electricity and corrosion because some portion of this unit will always remain submerged in corrosive working fluid like electrolytes. There is a provision for holding the workpiece rigidly with the help of two small screws and clamps in the housing. Out of these two screws, one is coupled to the positive terminal of the power supply system through the workpiece and the negative terminal to the wire electrode. The rigid stand is bolted down firmly to the machining table.

(ii) Fluid flow circulation unit

The main machining chamber which contains the workpiece is connected to the electrolyte chamber through a flow control valve and a rotameter is attached to the flow system for flow rate measurement through which electrolyte flows from flexible hose pipe to the machining chamber to perform WECM operation. The chamber size is kept optimum by considering the maximum size of the workpiece to be accommodated and the economical and judicious use of working media. During the WECM process, a controlled flow of electrolyte is maintained with the help of a motor pump with filter and flow control valve. For WECM operation, the electrolyte is used as a working medium in which the wire electrode tool is just dipped into the electrolyte and fed forward for the machining.

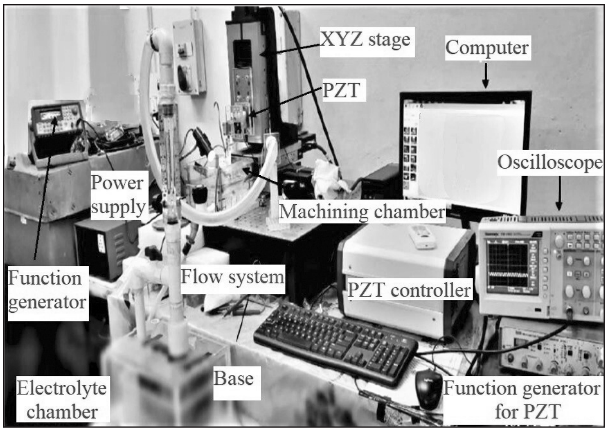

Fig. 1. Photographic view of WECM system.

(iii) Power supply units

The power supply rating of WECM is different for micromachining; hence separate power supply unit is required. During WECM, a pulsed DC power supply (Matsusada DOA75) is used to maintain constant polarity. The main input available power supply line has 3-Phase, 440V, AC. The reduction of input voltage and conversion of it from AC to DC has been achieved by the pulsed power supply. The available power supply has a voltage in the range of -75 to +75V and a current rating of up to 4A with 300W maximum power output. To generate the required nature of pulses, a pulse generator unit is used. A function generator (Agilent 33250A) is used to know the nature of the pulse and to monitor the machining conditions.

3. Experimental Planning

As we know WECM process is generally applied for machining electrically conductive materials. We realized that machining nitinol shape memory alloy without affecting original properties is a bit difficult task due to unique material properties. As in the case of WECM, the wire electrode never comes in contact with the (usually conducting) workpiece. But while machining metallic components, this rule is not followed due to changes in process parameters and energy interaction behavior. Because it is observed that as soon as the wire electrode touches the workpiece, the system draws more current from the power supply which starts the generation of stray current effect and micro-sparks at the wire electrode and workpiece interface takes place in a narrow IEG, which stops the further machining process. The workpiece material used for this experimentation is a nitinol shape memory alloy of 120 µm thickness made by Nexmetal Corp. Inc. USA. An initial IEG of 100µm between the wire electrode and workpiece is used and tried to maintain throughout experimentation. After the machining is over, the observations of micro-slits are captured with the help of an optical microscope. After WECM, to ameliorate the machining accuracy, the WECM process needs to be carried out in a sequence of process parameters. For this, an individual WECM power supply was brought into action, and a dedicated vibration-assisted axial nozzle jet flow system has been developed (Besekar & Bhattacharyya, 2021). After making these alterations in the system, various parameters such as applied voltage, frequency, and duty ratio are set in the WECM power supply unit as shown in table1.

Table 1
Process parameters with their values.

Parameters	Values
Applied Voltage, V	5,7,10
Duty Ratio, %	45
Applied Frequency, KHz	250
Electrolyte Concentration (H_2SO_4), M	0.1
Wire Feed rate, µm/s	1.4,1.6,1.8
Electrolyte Flow rate, lph	5

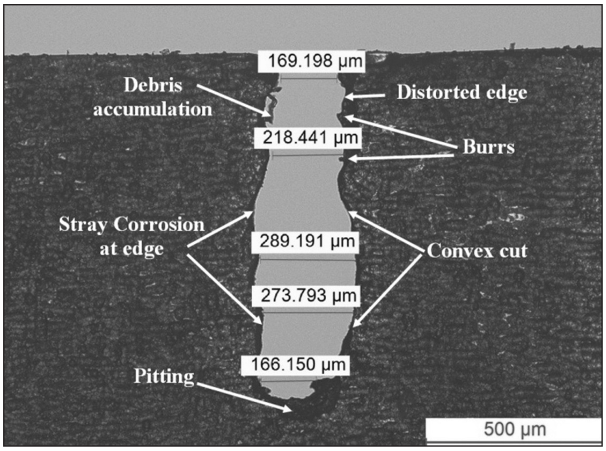

Fig. 2. Micro slit at 10V, 1.4 µm/s (Condition 1), convex profile with maximum overcut.

4. Results and Discussion

4.1. Energy interaction behavior during machining

For micro slits machining with a sufficient level while using WECM, the controlled relation between the pulse energy produced and their period for the workpiece is crucial. The applied voltage, pulse frequency, and duty ratio in WECM are primarily responsible for controlling the input energy. According to past research studies, pulse voltage is the most influencing process variable that has a significant impact on WECM performance. The interaction times for pulse energy are controlled by the feed rate. A series of exploratory experiments were carried out to examine the pulse energy interaction behavior during the fabrication of micro-slits with WECM. These studies altered the applied voltage from 5 to 10V and the wire feed rate from 1.4 to 1.8µm/s (which regulates the energy interaction duration). The fabricated micro slits at different parametric conditions of pulse voltage and wire feed rate, each of which defined the individual energy interaction behavior were presented as follows:

- High pulse voltage and low wire feed rate (Parameter Condition 1)

The set of parameters i.e. 10V and 1.4µm/s that apply to condition 1 fabricated micro-slits result in the largest amount of anodic dissolution as shown in fig.2. Thus, it can be deduced that the parameter combination will produce the most pulse energy due to the high pulse voltage. The material removal rate is high with the rise in anodic dissolution rate due to an increase in machining current at high pulse voltage. Also, the machining gap increases with more electrolysis products but machining stability got disturbed due to the low wire feed rate resulting in poor machining accuracy. The fabricated micro slits have maximum overcut which shows distorted edges with burrs and debris accumulation near the edges. Also, the profile of the micro slit has a convex cut with a more stray corrosion effect, and pitting was observed near the edge of the machined microslit.

The wire moves slowly at low feed rates. As a result, after the initial anodic dissolution, there are significant working gaps between the wire electrode and the work surface. More gas bubbles can gather around the wire electrode at narrow IEG. The intensity of dissolution grows at a feed rate of 1.4 µm/s and high applied voltage. Additionally, the intensity of dissolution diminishes as the feed rate rises. However, the frequency of micro-sparks increases.

- High pulse voltage and high wire feed rate (Parameter Condition 2)

The micro slit machining with high pulse voltage and high wire feed rate shows reduced slit width with improved homogeneity as compared to the condition 1 shown in fig.3. This is because the current increases at high pulse voltage increase the number of electrolysis products. At the same time, the high wire feed rate showed the effective renewal of electrolysis products from the narrow IEG resulting in a straight profile with reduced overcut.

The pitting and stray corrosion effects are also very low which shows a need for a high wire feed rate with high pulse voltage for better machining. On the other hand, it was discovered that the wire electrode's surface was damaged as a result of the process parameters i.e. 10V pulse voltage and 1.8µm/s wire feed rate producing an excessive amount of pulse energy. It appears that a high feed rate doesn't give enough time for the pulse energy needed for material removal to be released. The work material sustains mechanical damage at the same time as the wire electrode with the high feed rate comes into touch with it.

- Medium pulse voltage and medium wire feed rate (Parameter Condition 3)

In condition 3, the medium pulse voltage produces moderate current with a limited dissolution rate near the machining zone at narrow IEG as compared to conditions 1 and 2. Also, it was difficult to flush away the dissolved products due to the medium wire feed rate at this condition and the inter-electrode gap condition may become unstable. The parametric values that integrated the effects of the applied voltage and feed rate produced zigzag profiles of microslits with increased overcut and reduced accuracy compared to condtion 2. While the pulse energy interacted in such a way as to produce micro-slits with zigzag profiles for applied voltage at 7V and wire feed rate at 1.6µm/s with pitting and stray corrosion as depicted in fig.4.

In this investigation, variable pulsed DC signals were used to analyze the energy interaction between the wire electrode and the work material. Due to the theory of electrochemical double layer and the availability of the same input power, in the beginning, the effect of charging voltage for material removal is the same for all

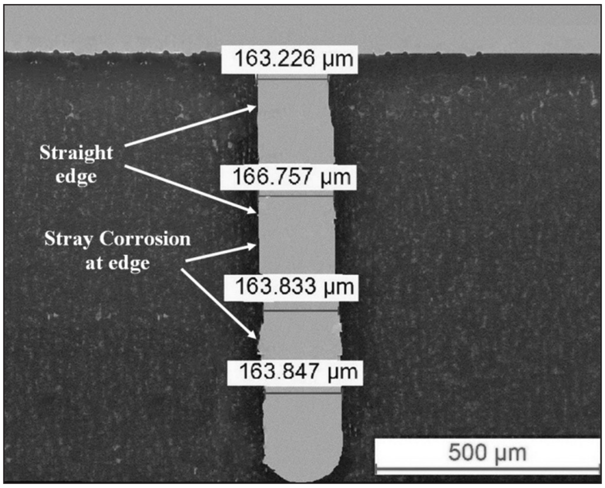

Fig. 3. Micro slit at 10V, 1.8 µm/s (Condition 2), straight profile with reduced overcut.

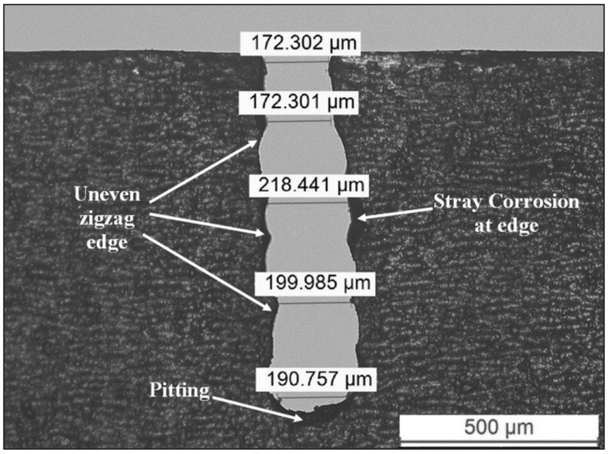

Fig. 4. Micro slit at 7V, 1.6 µm/s (Condition 3), zigzag profile.

conditions. Therefore, the distance between the wire electrode and the work material also changes as the feed rate changes. This alters how electrolysis products form and the properties of dissolution. It was shown that the strength of dissolution diminishes as the feed rate increases. The development of hydrogen gas bubbles is the cause of this which affects the current density distribution due to the electric field in the machining zone. Also, the removal of electrolysis products from the narrow IEG creates difficulty due to the formation of an oxide layer on the machined surface. This result in micro sparks due to the occurrence of electrical discharges with a reduction in homogeneity and obtained zigzag profile of fabricated microslits.

- Low pulse voltage and low wire feed rate (Parameter Condition 4)

The homogeneous micro-slit with the lowest slit width has been fabricated with the parameter

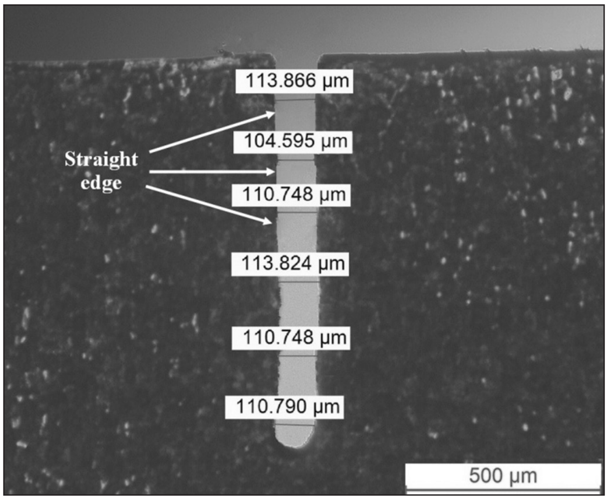

Fig. 5. Micro slit at 5V, 1.4μm/s (Condition 4), straight profile with minimum overcut.

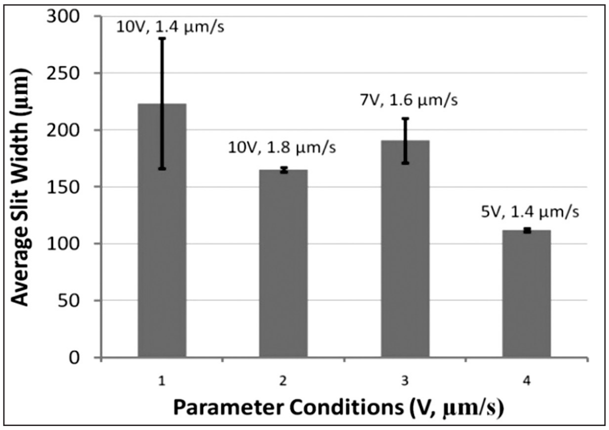

Fig. 6. Influence of pulse voltage at different positions of slit width.

condition of 5V pulse voltage and 1.4 μm/s wire feed rate as shown in fig.5. A feed rate effect is lower slit-width overcut with improved homogeneity at this condition due to narrow machining gap with limited current, proper dissolution rate and effective renewal of electrolysis products which further improves the stability of machining process and obtained straight microslit profile with minimum overcut. But past 1.4μm/s wire feed rate, homogeneity of micro-slits reduces with a detonation in wire feed rate. This is because the increase in feed rate in narrow IEG results in fewer periods of energy release in the machining zone. This in flip decreases the release frequency and intensity. Thereby it produces a small quantity of pulse power in the machining zone. This is inadequate to distribute uniform current density on the workpiece surface. Thus, the wire electrode makes direct contact with the workpiece surface at narrow IEG and affects micro-sparks because of immoderate mechanical forces exerted over the machining zone.

4.2. Influence of energy input parameter on slit width

The power interplay behavior is accountable to generate the special slit profiles at some stage in the WECM process as per the above discussions on initial experiments. The effect of the most influencing energy input parameter i.e. pulse voltage at varying feed rates on slit width at different parameter conditions shown in fig.6.

Experiments were conducted with pulse voltage of 5, 7, and 10V with varying wire feed rates. It is observed that the homogeneous micro slit of nitinol SMA has been fabricated at 10V, 1.8 μm/s and 5V, 1.4 μm/s at parameter conditions 2 and 4 with an average slit width of 165 μm and 111 μm a standard deviation of 2.11 μm and 1.68 μm respectively. It shows that the high pulse voltage with a high wire feed rate and low pulse voltage with less wire feed rate results in even energy distribution which is responsible to obtain homogeneity in the fabricated micro-slit. However, very high pulse voltage leads to an increase in slit width due to more energy density distribution in narrow IEG as compared to low pulse voltage conditions. Further, the experiments were carried out with 10V, 1.4 μm/s and 7V, and 1.6μm/s at conditions 1 and 3 has seen more variations with an average slit width of 223 μm and 190 μm a standard deviation of 57.24 μm and 19.57 μm respectively. It shows that the high pulse voltage with low feed rate and medium pulse voltage and wire feed rates results in uneven energy distribution which is responsible to obtain uneven edges in the fabricated micro-slit. The experiments at 5V pulse voltage with 1.8 μm/s wire feed rate resulted in the formation of micro-pits due to heavy micro-sparks during machining which stops further anodic dissolution and material removal. Below 5V pulse voltage and above 1.8 μm/s wire feed rate, no anodic dissolution takes place. The experiment results revealed that the increase in pulse voltage with a higher feed rate reduces slit width but very high feed rates and very low wire feed rates reduce the homogeneity and surface quality of the fabricated micro-slits of nitinol SMA.

5. Conclusions

Micro-slits of nitinol shape memory alloy have been fabricated by using a developed WECM setup. The energy interaction behavior during the fabrication of micro-slits has been experimentally investigated using the WECM process and conclusions drawn as follows:

- The experiment results revealed that the high pulse voltage i.e. 10V with a higher wire feed rate i.e. 1.8 µm/s reduces slit width but the low wire feed rate i.e. 1.4 µm/s results in distorted edges and more overcut with burrs and debris accumulation near the edges with more stray corrosion and pitting.
- The micro slit fabricated at 7V and 1.6µm/s results in uneven energy distribution which is responsible to obtain uneven zigzag edges in the fabricated micro-slit.
- The lowest average slit width of 111µm with 1.68 µm standard deviation has been obtained at 5V pulse voltage and 1.4 µm/s wire feed rate which shows better homogeneity of micro slit of nitinol SMA.
- The release of unpredictable and high pulse energy over the work material and very low and very high wire feed rate reduces the homogeneity and surface quality of the fabricated micro-slits of nitinol SMA.

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