euspen's 17th International Conference & Exhibition, Hannover, DE, May 2017
www.euspen.eu

Influence of dielectric fluid and tool electrode choice on micro-EDMed nitinol surface integrity

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Abstract.
The nature and quality of the machined surface plays a paramount role in biomedical applications owing to the inevitable interaction between implants and body cells. Implant surface roughness alters or defines biological responses of tissues that are in contact, a critical factor in the successful application of the implant. Moreover, concerns remain over the release of carcinogenic nickel ions especially after fretting wear, which is largely influenced by the surface roughness among other factors. These challenges, together with the aim to improve machining efficiency are the motivation for this study. With accuracy oriented applications in mind, Nitinol is machined with a constant low discharge energy whereas the voltage is varied widely. Synthetic dielectric oil and deionised water are used as the dielectric fluids whereas tungsten carbide, copper and nitinol are the tool electrodes applied. Material removal rates, tool wear rates and surface quality are recorded and the machined surface composition analysed. Suitable tool electrodes as well as dielectric fluid are suggested for micro-EDM of nitinol for medical applications.

Nitinol; micro-EDM, surface roughness, surface composition, finishing processes

1. Introduction

Named after its constituent metals and the laboratory where it was discovered, Nitinol (**Ni**ckel **Ti**tanium **N**aval **O**rdinance **L**aboratory) is an alloy that has found numerous applications in the medical field including neurology, orthopaedics, interventional radiology and cardiology. It is widely used to make self-expanding implants and can also be used to manufacture self-locking and self-compressing implants [1]. These applications make use of nitinol's special properties namely shape memory and superelasticity. Moreover, nitinol has excellent fatigue resistance and biocompatibility.

1.1 Why µEDM?

Though conventionally machinable, processes like grinding and turning produce a lot of heat, tool wear and generate a lot of mechanical stresses owing to the material's superelasticity. To cut it, one has to overcome the stress induced martensite phase. This challenge intensifies with high aspect ratio and surface quality demands associated with most of nitinol's applications thereby rendering conventional means uneconomical. Micro-EDM is a suitable process for machining nitinol [2] and can therefore help solve this challenge. In µEDM, controlled material removal is achieved through electrical sparks between a tool and workpiece electrode in the presence of a dielectric fluid. Its non-contact nature results to no mechanical forces, thus supporting miniaturization. Laser, µEDM commercial competitor has an inferior accuracy and results to a larger heat affected zone [3].

1.2 Need for surface roughness analysis

Among other causes, nitinol fretting wear during the products lifespan can result in the release of carcinogenic, undesirable nickel ions in the body [4]. Friction conditions, which are largely influenced by the surface roughness, have a huge impact on fretting wear [4]. Moreover, in medical applications, nitinol's surface roughness affects the interaction between body cells and implants, since the roughness modulates the biological response of tissues in contact with the implant [5]

1.3 Role of dielectric and tool electrode

Apart from providing the medium for the plasma to grow, dielectric fluid helps to cool the machined surface and flush off debris. Likewise, the tool electrode is not only key in realising the intended part profile, but its thermal conductivity, electrical resistivity and melting point have a considerable effect on the process.

2. Methodology

Bores with an intended depth of 0.1 mm were machined on a nitinol sheet using 0.5 mm tungsten carbide (WC) and copper (Cu) electodes. Sarix SX-100 high precision µEDM machine was used to carry out experiments using Hedma 111® oil whereas Sarix T1-T4 machine was used for experiments using deionised water (DI H_20) dielectric fluid. A 0.5 mm square nitinol electrode was used to machine extra bores for purposes of surface composition comparison. For each experiment, machining time, change in tool electrode length after machining (tool wear) and bore diameters were measured and used to calculate both material removal rates (MRR) and tool wear rates (TWR) using Equation 1 and 2 respectively.

$$MRR = \frac{\pi r^2 h_1}{t} \quad (1) \qquad TWR = \frac{\pi r^2 h_2}{t} \quad (2)$$

Where r denotes the bore radius, h_1 the actual bore depth, h_2 the tool wear height and t the machining time.

Exact bore diameters were measured using a Nikon MM-400 optical microscope. Afterwards, a Keyence VK-9700 3D laser scanning microscope was used for bore surface characterization which consequently enabled the measurement of surface roughness using both MountainsMap® scanning topography software and Keyence's analysis module. Finally, Scanning Electron Microscopy (SEM) and Energy-dispersive X-ray spectroscopy (EDX) methods were used to establish the constituent elements on the sample's surface.

3. Results and Analysis

3.1 Surface quality analysis

As shown in figure 1 and table 1, surfaces machined using oil dielectric had better surface quality than those machined using DI H_20. Cu electrode in conjunction with oil dielectric fluid produced the best surface roughness value (Ra = 0.09 µm) which was slightly better than the value (R_a = 0.1 µm) realised using WC electrode and oil.

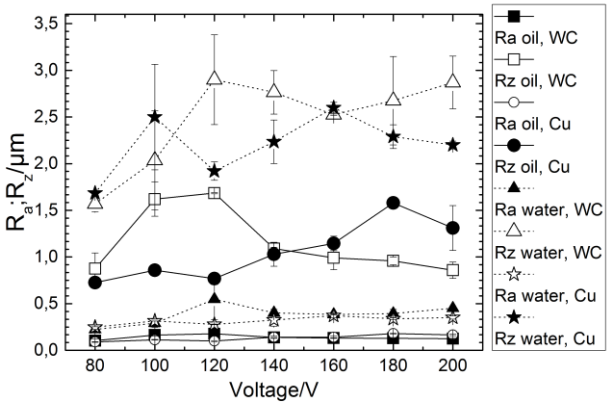

Figure 1: Influence of voltage, dielectric fluid and tool electrode on surface roughness.

This trend was consistent in most of the cases suggesting that copper/oil dielectric should be the preferred combination for best surface roughness results. However, water dielectric and WC produced a slightly better surface roughness value (R_a = 0.22 µm) as opposed to Cu (R_a = 0.25 µm). R_z values varied between 0.7 µm to 2.8 µm and were characterised by large standard deviations.

Table 1: R_a/R_z values for different electrodes and dielectrics.

Electrode material	Dielectric fluid	R_a/µm	R_z/µm	Open circuit voltage/V
Tungsten carbide (WC)	oil	0.10	0.86	80
	DI H_20	0.22	1.57	80
Copper (Cu)	oil	0.09	0.73	80
	DI H_20	0.25	1.69	80

3.2 Surface compositional analysis

As shown in table 2, elemental surface composition analysis reveals that constituent elements of the electrode remain on the machined surface.

Table 2: Percentage elemental surface composition.

Electrode material		WC		Cu		Ni	
Dielectric fluid		DI H_20	Oil	DI H_20	Oil	DI H_20	Oil
Elements	C	6	13	5	19	7	18
	O	13	0	11	0	14	0
	Ti	30	37	34	38	35	38
	Co	3	1	0	0	0	0
	Ni	42	44	45	41	44	44
	W	7	7	0	0	0	0
	Cu	0	0	5	3	0	0

Additionally, surfaces machined by DI H_20 had less carbon than their oil machined counterparts but had an oxide layer. Nitinol electrode machined surfaces had only carbon (oil dielectric) and carbon plus oxide (DI H20) as extra elements. This suggests that if applicable commercially, they could reduce surface contamination caused by using dissimilar electrodes.

3.3 MRR/TWR analysis

As shown in figure 2, deionised water produced higher MRR and TWR than oil dielectric for similar voltage settings. Apart from 80 V and 100 V, water dielectric fluid settings which produced peculiarly large MRR, the rest of the graph reveals a slightly higher MRR while using WC electrode, suggesting that WC should be the preferred electrode when MRR maximization is of interest.

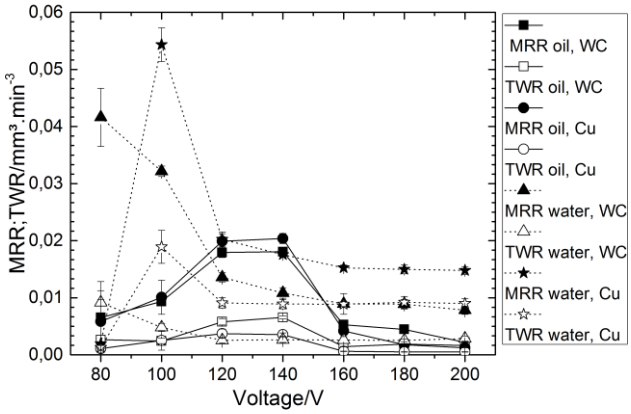

Figure 2: Influence of voltage, dielectric fluid and tool electrode on MRR and TWR.

4. Conclusions

The following conclusions can be drawn from this research;

- Deionised water produces higher MRR whereas oil produces better surface quality.
- Copper electrode produces slightly better surface finish whereas WC offers slightly higher MRR.
- Nitinol electrode has the potential to minimise machined surface contamination.

5. Recommendations

There is need to further investigate nitinol's abilities as a possible tool electrode material for machining nitinol.

Acknowledgement.

The authors are thankful to the German Academic Exchange Service, TU Chemnitz and NACOSTI for facilitating this research.

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