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Study on flushing condition for improving silver deposition in silver nano-powder mixed EDM

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Abstract

Silver nano-powder mixed electrical discharge machining (PMEDM) has demonstrated its applicability for antibacterial surface modification. However, previous PMEDM studies indicated that jet flushing leads to a low powder concentration in the spark gap, which was the main reason for a low deposited silver content. Internal flushing with different dielectric pressures was therefore proposed and will be investigated in this study. To do so, Ti-6Al-4V hollow tool electrodes with an outer diameter of 3 mm and an inner diameter of 2.5 mm are selected to machine Ti-6Al-4V samples. Silver nano-powders with a size of 50 nm to 60 nm are suspended in the hydrocarbon-based dielectric fluid at a 5 g/l powder concentration. Surface roughness and resulting silver content and distribution on the modified surface are analysed and discussed. Results show that internal flushing significantly increases the deposited silver content when high pressure of the dielectric fluid was applied. In addition, with careful control, the internal flushing is a promising strategy for improving the uniformity of the deposited silver distribution.

Keywords: PMEDM, antibacterial, flushing pressure, silver content, silver distribution

1. Introduction

Implant realated infections pose a major challenge for the medical implant industry [1]. Various technologies such as physical vapor deposition, chemical vapor deposition, plasma spraying and ion implantation have demonstrated their efficiency in antibacterial surface modification. However, these technologies have hitherto only been used for modifying the surface to achieve antibacterial characteristics. Consequently, additional manufacturing processes for shaping and structuring the implants are required.

Previous studies have demonstrated that powder mixed electrical discharge machining (PMEDM) using silver nano-powder is applicable to machine part geometries with the concurrent generation of antibacterial layers on its surface [2,3]. During the PMEDM process, silver from nano-powders was transferred to the modified layer to affect the bacterial adhesion and growth. It was reported that the deposited silver content plays a vital role on antibacterial properties. A higher silver content resulted in a decrease in number of *Staphylococcus aureus* bacteria [3]. In addition, compared to electrical discharge machining without powder, PMEDM can provide up to 3 times higher material removal rate [2,3].

The amount of powder in the spark gap plays an important role for the silver deposition. It has been indicated that suspending a higher powder concentration increases the silver content deposited on the modified layer as shown in Fig. 1. No remarkable effects on the roughness were observed [2,4]. Additionally, the spark gap was enlarged at a higher powder concentration [5]. Furthermore, it was reported that an increase of the discharge energy reduced the deposited silver content [4].

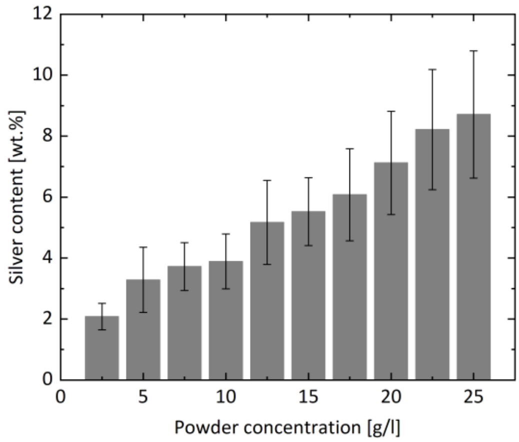

Figure 1. Influence of the powder concentration in the dielectric fluid on the deposited silver content. Machining conditions: lateral flushing, hollow tool electrode with outer diameter of 0.6 mm and inner diameter of 0.17 mm, 10 µJ discharge energy, positive tool electrode [4].

However, when using lateral flushing the deposited silver content was significantly influenced by tool electrode size. It was found that using a larger tool led to a decrease of the silver content deposited on the modified layer [2,4,6]. Silver content of 3.2% was deposited on the modified surface when using a 0.5 mm tool diameter and 5 (g/l) powder concentration [5], whereas the content of 1.2% was deposited when a tool diameter of 5 mm and a higher powder concentration of 18 g/l were applied [2]. This is due to the fact that there are challenges in transporting the suspended silver powder particles into the narrow spark gap when using lateral flushing. The ultrasonic vibration has been used during the PMEDM process to assist the particle transportation. However, a negligible influence on the powder amount in the spark gap has been reported [6].

Consequently, internal flushing is investigated in this study to increase the deposited silver content on the modified surface. In addition, the silver distribution will be analysed and discussed as the basis for further studies in generating more homogeneous distributions of silver with PMEDM.

2. Methodology

Schematic showing the difference between lateral flushing and internal flushing is represented in Fig. 2.

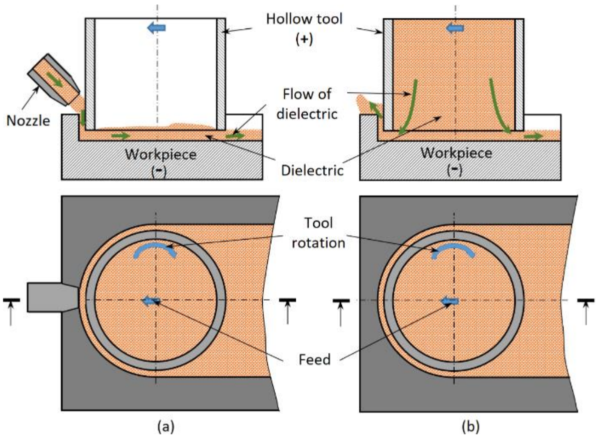

Figure 2. Schematic showing the difference between (a) lateral flushing and (b) internal flushing

It can be realized that the dielectric medium is provided from a tool´s side and has a long trip for the transportation within the machining gap if using lateral flushing. Additionally, a so narrow gap size [7] and the release of gas from the gap restrict the transportation of the suspended powder, which significantly affects the actual powder concentration in the machining gap. In the case of internal flushing, the dielectric medium is pressed through the hollow tool from inside to outside, thus facilitating the powder transportation through the spark gap. Therefore, the actual powder concentration in the gap can be significantly increased.

Ti-6Al-4V, owing to its excellent properties for medical implants including biocompatibility, corrosion resistance and high fatigue strength was used as workpiece material. Concerning the deposition of tool material on the workpiece surface, for tool electrodes the same material Ti-6Al-4V was chosen in order to affect the basic material as low as possible. The applied experimental conditions are given in Table 1.

Table 1 Experimental conditions

Parameter	**Value**
Machine	Sarix T1T4 µ-EDM machine
Workpiece	• Material: Ti-6Al-4V • Size: 14 mm x 12 mm x 1 mm
Tool electrodes	• Outer diameter 3 mm, inner diameter 2.5 mm • Rotation speed: 300 / min • Material: Ti-6Al-4V
Dielectric fluid	HEDMA111 oil
Flushing pressure	4 bar and 7 bar
Discharge energy	55 µJ
Polarity	Positive tool electrode
Powder	• Material: silver 99.9% • Size: 50-60 nm • Concentration in dielectric: 5 g/l

A (3 x 10) mm² area with a depth of h = 45 µm was machined on each sample as shown in Figure 3.

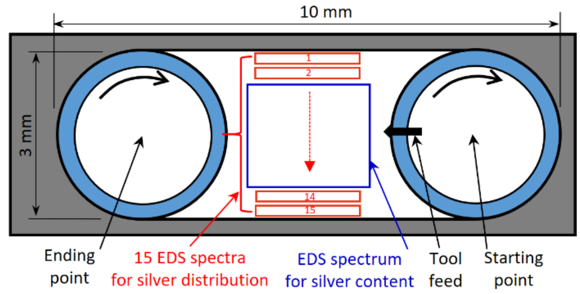

Figure 3. Schematic showing the geometry of the machined areas and locations for EDS spectra analyses of the silver content and silver distribution

After machining, each sample was cleaned in an ethanol filled ultrasonic bath at room temperature then dried in air. The elemental composition and mapping of the modified surfaces were analysed using energy dispersive X-ray spectroscopy (EDS). The surface topography was analysed using scanning electron microscopy (SEM). A spectrum of approx. (2 x 2) mm² was analysed on each surface to analyze the average deposited silver content in the modified layer, whereas 15 smaller spectra numbered from 1 to 15 were analysed to evaluate the distribution of silver contents perpendicularly to the tool feed direction.

To analyse the surface roughness, a Keyence VK9700 confocal 3D laser-scanning-microscope was used. From the detected surfaces, the roughness values were analyzed by utilizing MountainsMap 7.4 scanning topography software. For each sample, five surface roughness measurements were performed with the evaluation length of 1.25 mm and the cut-off length of 0.25 mm. Three samples of each machining condition were analyzed to calculate the average value and standard deviation.

3. Results and discussions

3.1. *Surface quality analysis*

The influence of flushing pressure on surface roughness of Ti-6Al-4V workpiece surfaces is presented in Fig. 4.

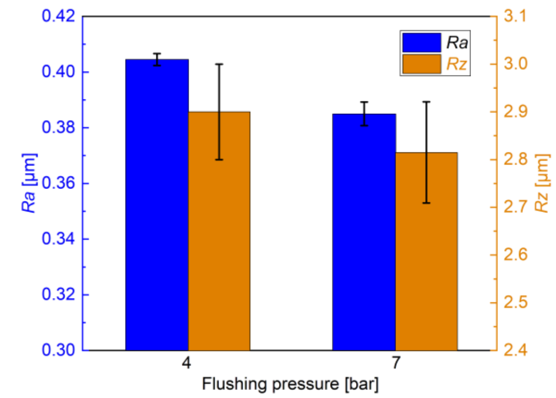

Figure 4. Effects of the flushing pressure on the surface roughness

The roughness of the modified surface is reduced when applying a higher pressure of the dielectric fluid. It may be a result of a better flushing condition, whereby the use of a higher flushing pressure provides more fresh dielectric fluid, which helps to faster cool down the modified surface and to faster flush the debris out of the spark gap. Short-circuiting is therefore reduced.

3.2. *Average content of the deposited silver*

Figure 5 shows the effect of flushing pressure on the deposited silver content of the modified surfaces.

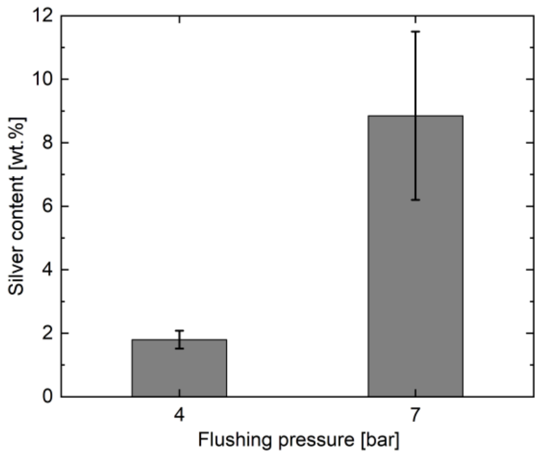

Figure 5. Deposited silver content on workpiece surfaces for different flushing pressures

The deposited silver content was significantly increased when using higher dielectric fluid pressure. The silver content of (1.80 ± 0.3) % is deposited on the modified layer with the utilization of 4 bar, whereas (8.85 ± 2.65) % was deposited, when a pressure of 7 bar is applied.

It can be realized that by applying internal flushing with suitable pressure, the silver content deposited on the modified layer can be adjusted and remarkably increased compared to the results of lateral flushing conditions. For example, in comparison to using a smaller hollow tool (0.6 mm of outer diameter and 0.17 mm of inner diameter) with lateral flushing shown in Fig. 1, the deposited silver content with applying the internal flushing pressure of 7 bar in this study is 2.7 times higher when suspending 5 g/l powder concentration in the dielectric fluid. This is due to an increase of the powder amount in the spark gap when the internal flushing strategy is applied. Additionally, it can be seen that the silver content deposited on the modified surface when using 7 bar pressure and 5 g/l powder concentration in this investigation is similar to the use of the aforementioned smaller hollow tool with 25 g/l powder concentration. Therefore, the efficacy of silver deposition is significantly enhanced.

However, the utilization of a 4 bar pressure leads to a lower deposited silver content. A reduced amount of silver powder in the spark gap is assumed as the main reason [4]. It seems that silver powder still faces a challenge to get into the gap in this case. In addition, the amount of dielectric fluid is significantly decreased, which adversely affects the cooling effect as well as the flushing of debris out of the spark gap. Therefore, more debris could remain in the gap and more short-circuiting occurs.

3.3. Distribution of the deposited silver

The distribution of deposited silver over the modified surfaces is shown in Figure 6. The single silver contents were detected in the 15 smaller spectra introduced in Figure 3. It can be observed that when applying internal flushing with low pressure, the distribution of silver is homogeneous at (2.5 ± 0.3) % considering spectra 1 to 11. However, results of spectra 12 to 15 indicate a significant increase at the outer edge of the tool electrode. At high pressure, silver is only uniformly distributed with values of (4.15 ± 0.25) % from spectrum 1 to spectrum 4. However, the variation is more evident, and significantly raises up to 31.7% at spectrum 15.

The deposited silver content strongly depends on the amount of powder in the spark gap. It is assumed that the amount of powder is significantly influenced by local flushing conditions that vary at varying spark gap size. Especially in the experiments with a pressure of 7 bar, local changes of the spark gap size due to non-parallelism between the tool tip surface and the workpiece surface are supposed to have caused significant changes in silver distribution on the modified surface.

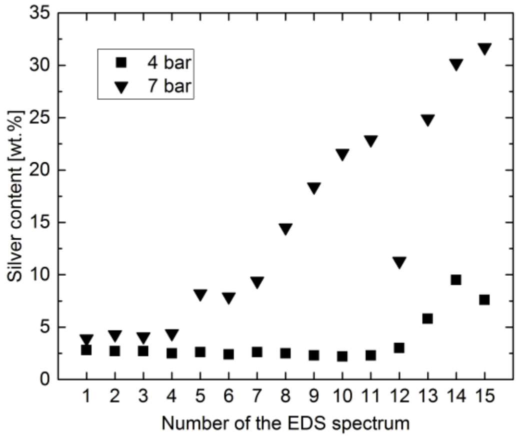

Figure 6. Distribution of deposited silver over the modified surfaces

Fig. 7 shows the change of the spark gap caused by non-parallelism of the tool tip surface and workpiece surface in this investigation as well as its effect on the flow of dielectric fluid and the amount of silver powder in the spark gap.

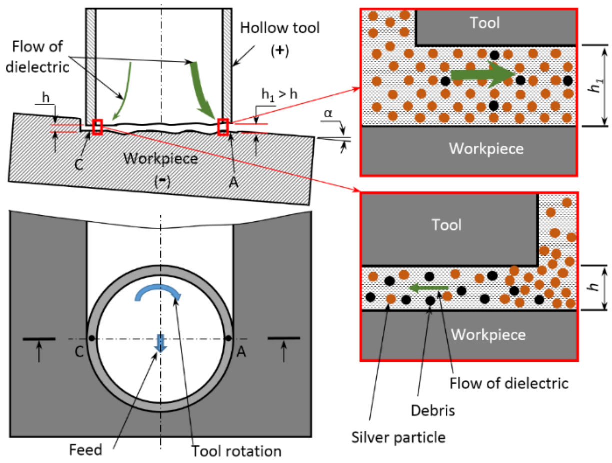

Figure 7. Change of the machining gap caused by non-parallelism of tool tip surface and workpiece surface, effects on the dielectric flow and the amount of silver powder as well as debris particles in the gap. Thicker arrows mean higher flow rate. Points C and A are positions of the analysed spectra 1 and 15, respectively

Due to this non-parallelism, the gap at point A is enlarged compared to the gap at point C, resulting in a higher dielectric flow rate at point A, which enhances the flushing condition and supplies more silver particles to the spark gap. Therefore, the amount of silver powder in the gap at point A is higher.

In addition, silver powder seems to face a challenge to get into a so narrow spark gap of (5…10) µm [7]. It leads to a significant reduction of the powder amount in the gap at point C resulting in low deposited silver content. The utilization of 7 bar pressure significantly enhances the flow of dielectric fluid and reduces the powder congestion, therefore increasing the average deposited silver content. Additionally, by using higher pressure, the influence of the gap change on the silver powder amount is more obvious. The amount of silver powder in the spark gap tends to increase from point C to point A, resulting in the increase of the deposited silver content from spectrum 1 to spectrum 15 shown in Fig. 6 in the case of using 7 bar.

Effects of the flushing pressure on the distribution of the deposited silver were analysed by silver mapping at different areas of modified surfaces as shown in Figure 8. It can be observed that with different dielectric pressures, silver was transferred to whole analyzed workpiece surfaces.

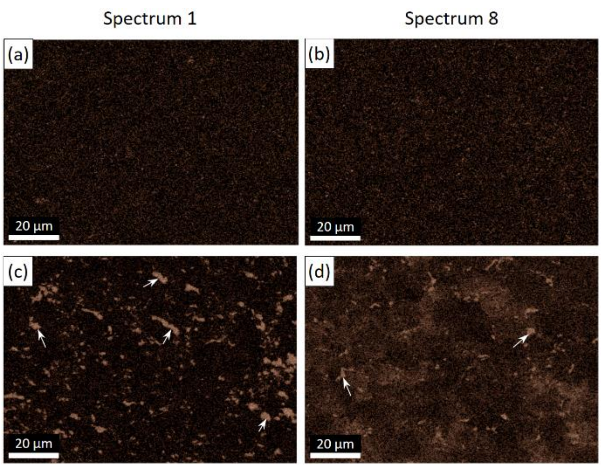

Figure 8. Silver mapping of workpiece surfaces modified using 4 bar (a-b) and 7 bar (c-d) of the dielectric pressure. Arrows point on the areas wih silver clusters

The application of a high dielectric pressure (c) and (d) shows clear effects on the silver distribution whereby silver was more densely distributed. This is due to a larger amount of silver powder in the machining gap. However, various silver clusters were deposited to the surfaces.

Comparing spectra 1 (left) and 8 (right), the silver distribution of the modified surface is relatively similar with 4 bar pressure, but obviously different with the pressure of 7 bar. Previous studies have shown that silver is transferred to modified surfaces as layers resulting from alloying and spattering effects [4,6]. Spattered silver is displayed as silver clusters shown in Fig. 8. For detailed analyses of these effects and the resulting topographies, SEM images of the modified surfaces were captured as presented in Figure 9.

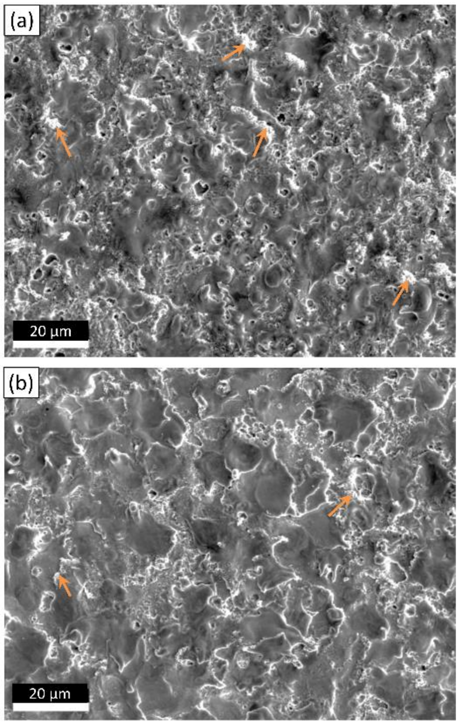

Figure 9. SEM images of workpiece surfaces modified using 7 bar pressure: (a) spectrum 1 and (b) spectrum 8. Orange arrows point on the regions (identical areas to Fig. 8) with spattered silver

It can be seen that a large amount of silver was deposited in the spattered layer of the modified surface when 7 bar pressure was used. With the pressure of 4 bar, this phenomenon was not observed, as no silver clusters were detected in this case (see Fig. 8). In addition, from Fig. 9, it can be realized that the flushing condition was significantly enhanced at spectrum 8 compared to spectrum 1, due to an enlarged gap with high pressure resulting in a better dielectric flow. Therefore, the spattered silver is decreased.

4. Conclusion

In this study, PMEDM with cylindrical, rotating tool electrodes using internal flushing for the hollow tool with different dielectric pressures have been used to investigate their influences on the deposited silver content and its distribution. From the results, it can be concluded that:

- By using internal flushing with dielectric pressure of 7 bar, the deposited silver content is significantly increased compared to 4 bar pressure.
- The dielectric pressure and the spark gap size play a vital role in the amount of silver powder in the machining gap, which significantly affects the deposited silver content.
- It is possible to apply the internal flushing to improve the uniformity of the deposited silver distribution with careful control of the spark gap size and the parallelism of the tool tip surface with the workpiece surface.

5. Recommendation

Further studies are recommended to evaluate the possibility of the internal flushing condition on improving the uniformity of deposited silver. A negative tool electrode with careful control of the parallelism between surfaces of workpiece and tool should be used to machine with both single and overlapping machining lines.

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