Current and Power Peak Values in Plasma Electrolytic Polishing

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Abstract

Plasma electrolytic polishing (PeP) enhances the surface quality and performance of electrically conductive materials. Mostly it is used as an anodic process where the workpiece acts as the cathode. This process, however, faces challenges with high current peaks, particularly when polishing larger workpieces, due to the development of a vapor skin. This research examines how the rate at which the workpiece is immersed affects the current and power peaks overall power usage during the early stages of the PeP process, focusing on a microreactor mould insert. Through detailed experimentation and analysis, the study explores how adjusting the immersion speed can regulate the initiation phase of PeP, thus optimizing the process. Findings demonstrate that the highest current and power levels are not reached when the workpiece initially contacts the electrolyte, but rather when the electrolyte overflows the workpiece top. A technique of immersing the workpiece with the voltage already applied results in a significant reduction, more than 80%, in both peak current and average power, offering a new method to enhance the efficiency of the PeP process.

Keywords: plasma electrolytic polishing (PeP); peak current; average power; process initialisation

1. Introduction

Plasma electrolytic processes have attracted the attention of metal finishing industry due to their ability to significantly improve surface properties [1]. Among them, plasma electrolytic polishing (PeP) is a special case of electrochemical machining that requires high voltage and uses environmentally friendly aqueous salt solutions [2]. Material removal is a consequence of a special case of anodic dissolution [1],[3],[4]. The PeP process, first described in 1978 [5], is a surface treatment technology that leads to very smooth, high-gloss surfaces with improved corrosion resistance [6] and is a promising post-processing technology for additively manufactured parts [7].

The process takes place in a vat containing a material-specific aqueous electrolyte solution with low viscosity. Its conductivity is adjusted from 4 to 30 S.m^{-1} by adding up to 12 % of various salts and suitable complexing agents. The workpiece in the vat is anodically polarised; the voltages used are in the range of 180 to 400 V. In addition to the workpiece, there is a cathode electrode in the electrolytic cell. The surface ratio between the anode and cathode should be greater than 1:10 and the cathode does not have to resemble the geometry of the part; a ring or plate shape is common. The ratio is necessary to ensure the required current density for plasma formation on the anode surface. The relationship between current density and applied electrical potential must be set to adjust the process window to the electro-hydrodynamic area for the PeP process. There, caused by the process conditions, a vapour-gaseous envelope forms around the workpiece and a plasma layer is created. In combination with the *electrochemical reactions* such as (anodic) metal dissolution, (anodic) oxide formation, hydrogen formation and alkalisation, the *plasma reactions* such as ionisation of the vapour-gaseous envelope and hydrothermal reactions such as metal dissolution by metal-water reaction, lead to a removal of surface peaks and thus to a polishing of the part. The vapour-gaseous envelope results in the process surface temperature not significantly exceeding the electrolyte boiling temperature; hence during the process, the part reaches a maximum temperature of 120 °C [8].

Regardless of which material is to be polished, the current peak and the power that occur during the initialisation phase of the process must be taken into account. Namely, when a voltage is applied between the two electrodes submerged in an electrolyte, a high current peak is generated due to the high electrical conductivity of the electrolyte. When the vapour-gaseous envelope forms, the conductivity decreases considerably and the current drops to several amperes depending on the size of the workpiece surface [8]. The larger the workpiece surface, the higher the current and the power. This is also the case in the process initialisation phase when a vapour-gaseous envelope forms around the workpiece. In this phase, it is advantageous not to exceed the power required after the vapour-gaseous envelope has completely formed, i.e. during *stable polishing*. In extreme situations, the electrical power may be too high and fuses will switch off the power supply to prevent damage to the power supply and/or electrical wiring. The most common solution in practise is to initiate the process by slowly immersing a workpiece in an electrolyte to allow time for the vapour-gaseous envelope to form and to avoid a large surface area being in direct contact with the electrolyte. The influence of the immersion speed on the electrical quantities and phenomena during the initialisation phase has not yet been systematically investigated.

In this paper, the effect of immersion speed (the workpiece velocity in *z* direction) on the peak current and average power is investigated in the case of a workpiece size corresponding to a microreactor baseplate [9] to be manufactured by laser powder bed fusion (PBF-LB/M) and polished by PeP [10]. We formulate the hypothesis that the highest power occurs when the workpiece encounters an electrolyte and forms a short circuit on a large surface before the

vapour-gaseous envelope forms. The peak current occurring there is very important. We also try to determine the highest immersion speed at which the electrical power during process initialisation does not exceed the power required for stable polishing. Based on the results, the hypothesis is rejected but the appropriate immersion speed is successfully defined.

2. Materials and Methods

The experiments were carried out with the 80 kW PeP plant (Leukhardt Schaltanlagen GmbH, Germany), which can supply 150 A and voltages in the range from 150 to 380 V. The machine has a z stage and enables the control of the workpiece movement in z direction and the setting of the immersion speed in the range from 0 to 500 mm·s^{-1}. The temperature and concentration of the electrolyte play an important role in the PeP process. To create the same conditions in all experiments, sodium carbonate (Na_2CO_3) dissolved in water was used as electrolyte to avoid material removal on the workpiece. We kept the temperature of the electrolyte at 80 °C and the concentration of sodium carbonate at 0.55 M. The temperature was controlled by the Caso design TC2400 induction heating hob (Caso Gmbh, Germany). Due to water evaporation, the electrical conductivity was frequently monitored and maintained at 13.5 S·m^{-1}; fresh water was added when needed. The workpiece used for the experiments was the size of a mould insert for the mass production of microreactor units. It was a plate with a diameter of 40 mm and a thickness of 10 mm. The bottom surface was therefore 1256 mm^2 and the total surface area was 3768 mm^2. The material was stainless steel AISI 316L and its bottom surface was mechanical polished to mirror surface (Ra = 0.05 µm). Thus, a repeatable effective surface area as well as the wetting characteristics such as contact angle of the workpiece were maintained, making the experiments more repeatable and more under control. The workpiece bottom surface was parallel to the electrolyte surface during immersion.

To acquire the voltage and current signals, the Picoscope® 3205D oscilloscope (Pico Technology, UK) with a resolution of 8 bits at 1 GS·s^{-1} and a bandwidth of 100 MHz was connected to a PC (Linux OS with PicoScope® 7 oscilloscope software) via a USB cable. The voltage differential probe Testec TT-SI9101 (Testec Elektronik GmbH, Germany) with a bandwidth of 100 MHz was used with an attenuation ratio of 1:100 to reduce the input voltage to the oscilloscope. The current was measured with a Tektronix TCP303 current probe (Tektronix Inc., USA) with 15 MHz bandwidth and the ability to measure currents up to 150 A. The probe was connected to a Tektronix TCPA300 amplifier (Tektronix Inc., USA) with 100 MHz bandwidth. The entire setup is shown in Figure 1Figure 1.

The current and voltage waveforms were recorded in an oscilloscope buffer and transferred to the PC after acquisition. They were analysed in a Matlab® programming environment. Due to the relatively low resolution of the oscilloscope in the y-axis (8 bits), the voltage and current signals were first filtered using a Savitzky-Golay smoothing filter [11] with second-degree polynomial function, taking into account 0.02 ms before and after the observed sample on the signal. The filtered voltage and current signals were used to calculate the power signal.
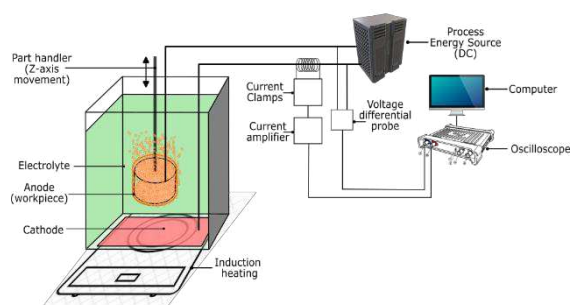

Figure 1: The acquisition system to monitor the voltage and current signals during PeP.

Two current peaks were identified in the initialisation phase of the process, namely when the workpiece and the electrolyte make electrical *contact* and when the electrolyte *splashes* onto the workpiece top surface. Within both time domains, the average power $\bar{P}$ was calculated as the energy within the time domain divided by the duration of the time domain t according to the equation

$$\bar{P} = \frac{1}{N}\sum_{i=1}^{N} U_i \cdot I_i \cdot \Delta t \; , \qquad (1)$$

where U_i is the voltage, I_i the current, i a sample number and N is the number of samples in the time domain. The average current and power during a *stable polishing* were also calculated for the last 0.5 ms of the signals. The standard deviation was calculated based on the variation of average power between repeated experiments.

The experiments were carried out at seven immersion speeds, namely 5, 20, 100, 200, 300, 400, and 500 mm·s^{-2}. Two additional experiments were carried out. In the first, the bottom surface of the workpiece was touching the electrolyte surface and the contact area was 1256 mm^2. In the second, the workpiece was fully submerged in the electrolyte and the contact area was 3768 mm^2. Most of the experiments were performed five times. The exceptions are experiments with velocity 500 mm·s^{-1} were performed three times, velocity 400 mm·s^{-1} ten times and with submerged workpiece only two times.

3. Results and discussion

The polishing process begins with a short circuit due to the high conductivity of the electrolyte liquid. Once the vapour-gaseous envelope has formed, the resistivity is increased and the current is reduced. The current peak level and the time of its occurrence depend on the immersion speed, as shown in Figure 2. Higher velocities lead to higher peak values and the time between the start of polishing and the peak value is shorter. The highest velocity the machine tool can deliver is 500 mm·s^{-1}. But even at this velocity, the current peaks are ten times lower compared to the current peaks measured when the process starts with a fully *submerged* workpiece or when the workpiece bottom surface is *touching* the electrolyte surface. The average current during polishing is calculated based on all acquired signals and displayed as a blue, continuous horizontal line over the entire time span. The dotted lines represent the corresponding standard

deviation. When immersion speed below 100 mm·s⁻¹ is used, the peak values are lower than the average current during polishing, i.e. after the transient phenomena during initialisation of the polishing process. We can claim this as a general rule, but most likely for each shape and size of the workpiece there is the immersion speed that leads to a current and voltage in the initialisation phase comparable to *stable polishing*. The term stable polishing is used for the process after the immersion is completed, e.g. after 155 ms on Figure 3.
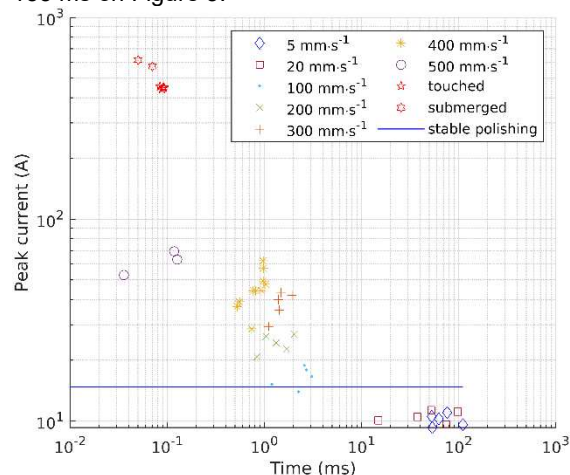

Figure 2: Current peaks in the contact time domain and the time of its appearance measured from the time when workpiece touches the electrolyte surface for various immersion speeds, when the workpiece position is fixed at touching the electrolyte surface, and when it is fully submerged.

At velocities above 100 mm·s⁻¹, the current peak during process initialisation is higher than during stable polishing. For a workpiece with flat and parallel top and bottom surfaces, the highest peaks are not observed when the workpiece comes into contact with the electrolyte, but when the electrolyte splashes over the top surface of the workpiece (Figure 3), which is an interesting result. The top and bottom surfaces of the workpiece are the same size and the entire bottom surface immediately causes a short circuit in contact with the electrolyte. Therefore, higher average power is expected during *the contact* with the electrolyte and not during *the splashing* over the workpiece top surface. However, it appears that the electrolyte flow plays an important role in the formation of the vapour-gaseous envelope at all immersion speeds (Figure 4). This should be taken into account when planning the PeP process, especially when polishing lattice structures [12].

The peak current increases at all immersion speeds examined, but the average power stabilises at v=300 mm·s⁻¹. It appears that the electrolyte flow does not change significantly at immersion speeds between 300 mm·s⁻¹ and 500 mm·s⁻¹ in terms of average power, but significantly enough to affect the peak current. At the velocities below 100 mm·s⁻¹, the peak current and average power during stable polishing are lower than these values. Both the current peaks and the average power play a decisive role for the process performance and they should be considered to avoid overloading of the PeP plant. Therefore, immersion speed below 100 mm·s⁻¹ is recommended for the given workpiece.

Even when polishing a small workpiece with 38 cm² surface area, the highest average power occurs when the process starts by submerged workpiece. The average power is 48.9 kW. When the process is initiated during immersion, the highest average power is identified during splashing and it is below 8 kW, which means a reduction above 80 %. Compared to the average power at the highest immersion speed, i.e. v = 500 mm·s⁻², the average power is significantly lower at low velocities, but much higher when the workpiece is touching the electrolyte surface during process initialisation (current peak more than 6 times higher and average power almost 3 times higher) or when it is fully submerged in the electrolyte (current peak more than 8 times higher and average power almost 6 times higher). Therefore, the slow formation of the vapour-gaseous envelope is crucial to keep these values as low as possible.
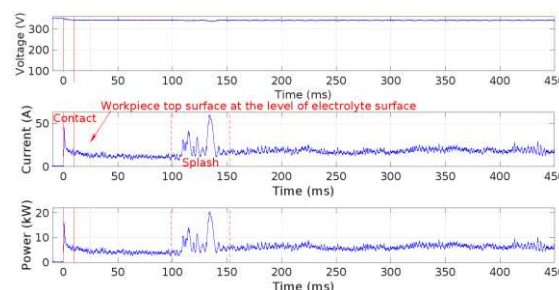

Figure 3: Waveforms at immersion speed 400 mm.s⁻¹ and current and power peaks indicated by red circles in contact and splashing time domain.
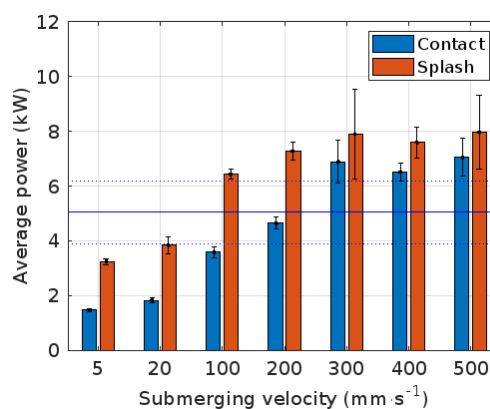

Figure 4: Average power for all immersion speeds in contact and splashing time domain. The blue continuous horizontal line represents the average power in stable polishing and the dotted lines its standard deviation.

4. Conclusions

Although the initialisation of the PeP process is carried out in practise by immersion the workpiece in the electrolyte, the influence of the velocity on the electrical parameters has not yet been investigated. Based on the results presented, the following conclusions can be drawn.

- The initialisation phase must be taken into account also when polishing relatively small workpieces. The process should be initiated during immersion of the workpiece and not only when the workpiece

is already submerged in the electrolyte, as current peaks of 600 A and an average power of 50 kW can be reached when polishing a workpiece with a surface area of 38 cm^2. If the process is initialised during immersion at any speed, the highest values occur in the initialisation phase during splashing: The current peak is below 80 A and the highest average power is below 8 kW, which corresponds to a reduction of about 90 % and above 80 %, respectively.

- When using lower velocities, no significant current peaks are observed. In the case of the workpiece of the size of a mould insert for microreactors, velocities below 100 mm.s^{-2} should be used. Such immersion speed during process initialization is not causing a significant increase of the machining time.

- In the case of workpieces with flat and parallel top and bottom surfaces, the splashing of the workpiece top surface by electrolyte causes higher current peaks and average power than in the contact of the workpiece and electrolyte at all velocities examined. This finding rejects the hypothesis that the highest power occurs when the workpiece comes into contact with an electrolyte due to a short circuit. The electrolyte flow therefore plays an important role in the formation of the vapour-gaseous envelope at all immersion speeds. This finding is important also when developing the PeP technology for polishing of lattice structures.

- Both the current peaks and the average power play a decisive role for the process performance and should be considered to avoid overloading of the PeP plant.

There likely exists the immersion speed for every shape and size of the workpiece that leads to the current and voltage signal in the initialisation phase comparable to these signals during the stable polishing. Initialization of the process by controlled immersion of the workpiece is one of the solutions to successfully start the polishing process without overloading the machine tool. There are also other solutions to slowly extend the vapour-gaseous envelope over the workpiece surface, which are going to be examined.

Acknowledgements

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