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Process analysis of plasma-electrolytic polishing (PeP) of forming tools

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Abstract
Plasma-electrolytic Polishing (PeP) is an innovative forceless ablation process based on environmentally friendly water-based electrolytes. Typical areas of PeP application are in deburring and surface smoothing for industrial, medical, micro- and nanotechnology and automotive/aerospace parts. In forming, a potential benefit of PeP surface treatment is to clean the tool surface for the forming process while at the same time polishing it, so that an optimal forming process can be designed. In the article, the basic principle is explained and questions that are still open are discussed. Plasma electrolytic Polishing is a very efficient process because very complex surfaces can be polished and the productivity of the process is very high. During the polishing process, the functional geometry of the forming tool is not impaired and comparably lower surface roughness is achieved than with competing polishing processes. The innovation potential can be demonstrated through PeP process analysis and selection of suitable process parameters.

Keywords Plasma-electrolytic polishing · Forming tools · Polishing process · Process analyses · Equivalent diagram · Ultra-sonic

Introduction

The surface finishing of forming tools represents an important manufacturing step. Milling is usually followed by a manual surface finish in order to gradually reduce roughness peaks. This ensures better flow behavior and less wear, longer tool life, higher productivity, less use of separating agents, better removability, and corrosion resistance. To achieve these advantages, unevenness after milling is first removed with grinding stones and then with increasingly finer abrasive paper. In this process, manual finishing of a drawing tool for large sheet metal parts can take up to 130 working hours, making this process one of the most costly and time-consuming in the production of forming tools. The biggest advantage of manual surface finishing is its high flexibility, as almost any type of geometry and material can be processed. On the other hand, besides the high cost, the process has technological disadvantages. It is subject to the fluctuations of manual work in terms of machining time, the surface quality achieved and the amount of material removed. The deviation from the nominal geometry, which is only a few hundredths of a millimeter after milling, is increased by the manual surface finishing. The polishing process is characterized by many influencing factors, as shown in Fig. 1, and sometimes leads to the fact that certain polishing processes must be disregarded [1].

The PeP process can offer significant advantages relating to a number of factors. It does not cause mechanical and thermal stress on the surface does not produce relevant changes in surface hardness, and it can be applied to complex surface geometries. Essentially, surface leveling occurs while maintaining the functional geometry [2, 3]. Tool wear approaches zero, with no need for a tool electrode matched to the workpiece. An equally important factor is that aqueous, non-toxic electrolytes can be used. In [1] there is a comprehensive overview of electrolytic plasma technologies and their boundary conditions. For example, the differences between Plasma Electrolytic Oxidation (PEO),

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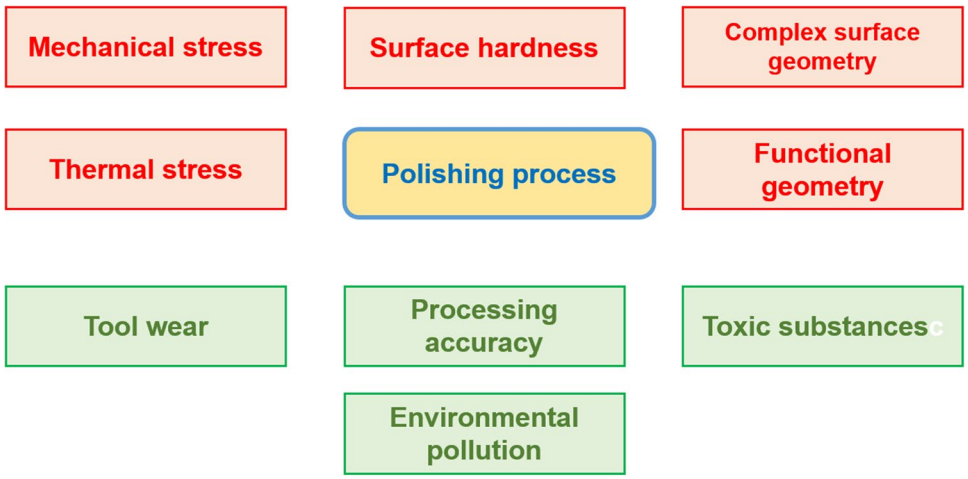


Fig. 1 Influence factors of the polishing processes

Plasma Electrolytic Coating (PEC), and Plasma Electrolytic Polishing (PeP) are presented. Ablyaz et al.[4] show how ED processed surfaces can be transformed into smooth and shiny surfaces by PeP. Melitis et al.[5] explain how the PeP process cleans the surface and by changing the electrolyte and voltage range at a changed current density, the surface is subsequently coated. Nestler et al. [6] show the variety of applications of the PeP process to produce high gloss surfaces especially in the medical field, which also has applications in the jewelry industry, the automotive industry, and environmental technology.

The fundamentals for PeP treatment are a classic electrolytic cell consisting of an electrolyte basin, electrolyte solution, anode, cathode, and a DC Process Energy Source. The workpiece is positively poled (anode) and the container wall is negatively poled (cathode). The electrolyte solution is an aqueous solution (water content approx. 95%) to which environmentally friendly conducting salts are added. By applying a voltage in the range of 180 - 350 V and immersing the workpiece in the tempered electrolyte solution, a gas/vapor envelope forms around the anode. Due to the high-energy input, ionization reactions take place in this vapor envelope, leading to the formation of a Plasma skin around the workpiece. Within the plasma zone, electrochemical as well physical and electrical interactions cause an all-around removal of the roughness peaks, which leads to the achievement of high gloss values and very low roughness values. Figure 2 shows an example of such an electrolytic cell for plasma electrolytic surface treatment.

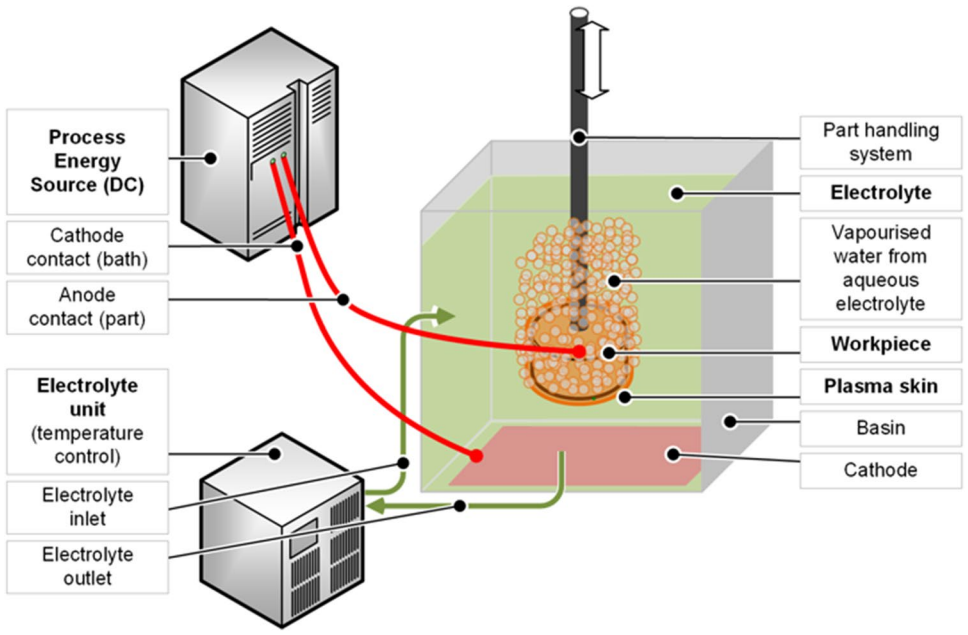


Fig. 2 schematic concept of an electrolytic cell for Plasma electrolytic Polishing

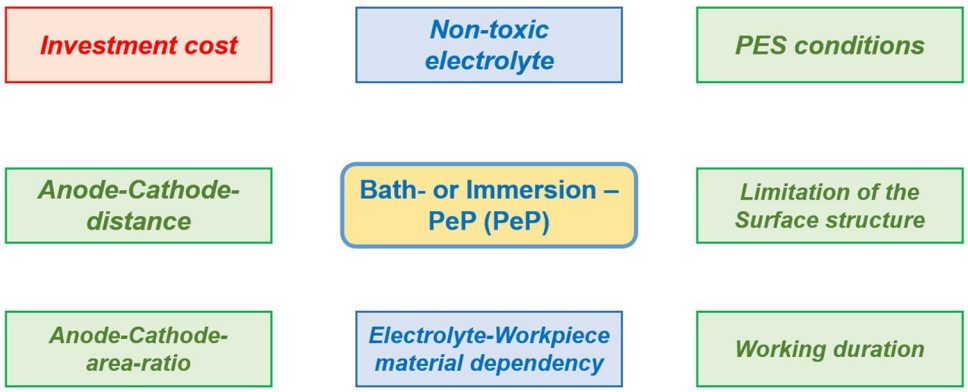


Fig. 3 Boundary conditions for the Plasma electrolytic Polishing

Modeling and process analysis

To determine the optimum process conditions of the PeP process in relation to the specific application, it is necessary to understand the process sequence. At the moment, it is possible to control it via current flow and voltage control. In order to assure a stable PeP process, the first thing to consider is the boundary conditions and their consequences.

Boundary conditions for the PeP

In Fig. 3 the relevant boundary conditions are compiled and described for immersion-based PeP. It has already been mentioned as an advantage that non-toxic aqueous electrolytes can be used for PeP. However, it is necessary to specify the electrolyte for different workpiece materials in order to achieve an optimal treatment result. Regarding the distance tool-workpiece, a very large distance is considered, which according to [1] allows observing the processes at anode and cathode separately. For most applications, it can also be assumed that the surfaces of the anode and cathode are very different. As a result, higher current densities act at the anode (workpiece) than at the cathode and closed process formations can occur around the anode during the stable polishing process.

Another boundary condition is determined by the load conditions at the process energy source (PES). For this purpose, it is useful to create an equivalent circuit diagram of the PES, connection requirements and process model (Fig. 4)**.** It is evident from this that the switch-on condition (resistance R_I) is significantly less beneficial in the immersed state than when it takes place outside the electrolyte and then the workpiece is immersed in the electrolyte. Then R_I is variable and the overshoot of the inrush current is significantly lower.

Analysis of the PeP-Phases

The PeP process can be divided into four important phases [8]. Figure 5 shows the most important case distinctions and the typical phase progressions regarding the process phases. The switch-on phase (I) determines the reliable design of the PES and its minimum load configuration. The most characteristic dependence results from the position of the workpiece in or outside the electrolyte when the operating voltage is switched on (Fig. 5A and B) and the immersion speed (B1 and B2).

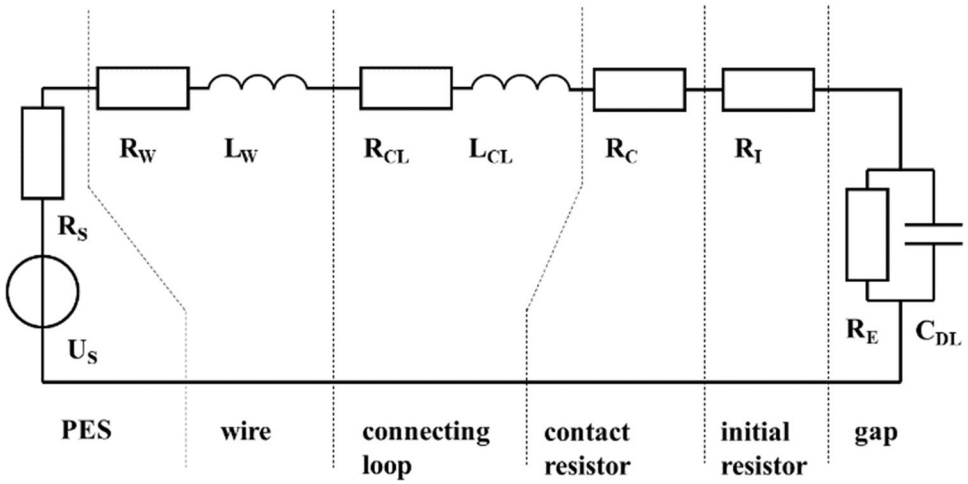


Fig. 4 Equivalent circuit diagram for the PeP process [7]

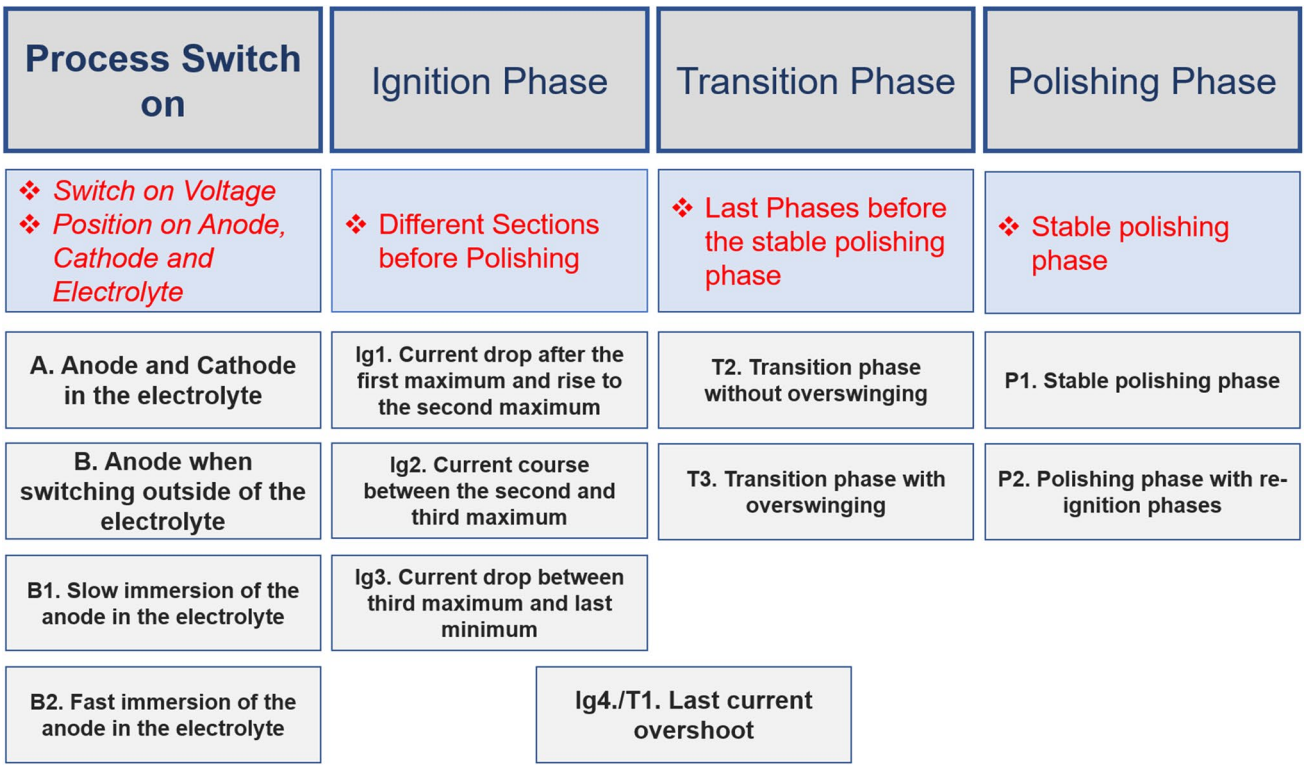
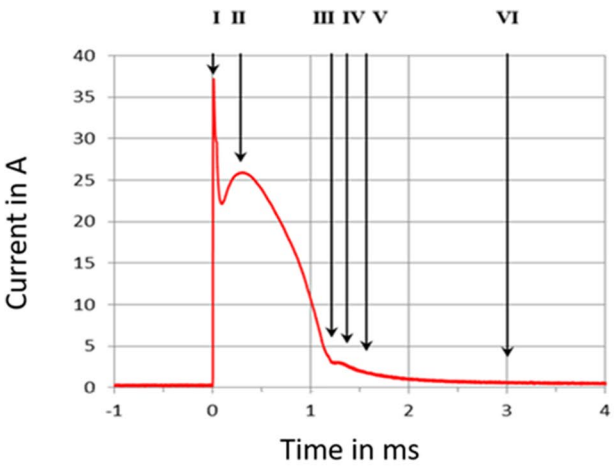


Fig. 5 Sub-Phases of the Immersion-PeP

In Fig. 4, this corresponds to the resistance R_I and the change in this value during the switch-on phase (I), which is reflected in Fig. 6 in the current sections I to II. In the ignition or initialization phase (II to IV), the necessary layers are formed on the anode. Gas formation already starts in phase I and turns into a closed plasma layer in the



R_I → Initial resistance (bath or air switch on)
Change of the DL-Impedance by immersion
R_{CL} → Connecting loop resistance
R_{Co} → Contact resistance (Anode)
R_E → Electrolyte resistance (Anode – Cathode)
R_{DL} → Double layer resistance
C_{DL} → Double layer capacitance
L_{CL} → Connecting loop inductance
R_s → PES inner-resistance
U_S → PES voltage source

$$\underline{Z} = \left(R_I + R_{CL} + R_{Co} + R_E + 2R_{DL} - j\frac{2}{\omega \cdot C_{DL}} + j \cdot \omega \cdot L_{CL}\right) \quad (1)$$

$$\rho = \frac{1}{(R_L + R_E + R_{Co} + 2R_{DL})}\sqrt{\frac{C_{DL}}{L_{CL}}} \quad (2)$$

Fig. 6 Current curve for the PeP-Process with impedance and overswinging [7]

initialization phase. The two sources of gas formation are electrolysis (cold gas formation) and, on the other hand, Joule heating at the anode surface (hot gas formation). According to [9], the conditions for hydrogen pyrolysis, operating voltage above 120 V and electrolyte temperature above 75 °C are also fulfilled for the stable PeP, which stabilizes the plasma region from the cathodic side.

The most important part, the initialization phase (III - V), determines how stable the polishing phase (after VI) is. The transition phase (V - VI) is strongly characterized by the initialization and the disturbing factors during the polishing phase.

Influence of the process parameters

As influencing factors, the operating voltage U_S and the electrolyte temperature T_{El} are mainly to be considered. These parameters can be primarily influenced by the PES or a separate temperature control.

Figure 7 shows the dependence of the PeP phases on the operating voltage in the course of the operating current in the range from 200 to 400 V. The voltages of 200 and 225 V show another strong increase of the operating current in phase IV, so that the stable polishing current can only be established after 3,5 ms and is still not certain for reinitializations. The maximum of section II (Fig. 6) shifts between 0,2 ms and 0,7 ms according to an exponential function $1/(e^{f(Z1,t)})$, while the minimum of section III changes according to the exponential function $1/(e^{f(Z2,t)})$. The stabilization onset varies between 0,7 ms and 1,4 ms and an ideal working voltage around 300 V emerges.

Looking at the current waveforms at 300 V and a very low connection inductance (2.9 mH) (Fig. 8), the sections I differ little from each other. The maximum II occurs fastest for 90 °C and the transition phase V already starts at 1,2 ms, while at lower electrolyte temperatures this phase extends to 2 ms.

Experimental set-up for forming tools

Test sample geometry

Forming tool The company µ-Tec GmbH provided a steel tool with structuring, which was taken from the common process sequence before the surface finish. The tool is made from the alloy 1.2083.

Model geometry with trench structure To study Plasma electrolytic Polishing in recesses, specimens were made out of 316 L (60 mm x 15 mm x 2 mm). Trenches of a depth of 1 mm and a width of 0,5 mm were milled into the specimens.

Plant engineering The test setup is carried out on a plasma polishing system from the manufacturer AMtopus GmbH & Co.KG (modified setup based on type FOH 80). The basic setup of the system can be seen in Fig. 9. The workpiece is attached and contacted to the mobile machine frame, which carries the cable to the anode. With the aid of the control system, this part of the machine can be moved in a vertical direction and thus different immersion depths in the bath can be realized. A magnetic sensor on the machine frame determines the variation of the immersion depth. The filling of the electrolyte bath is ensured with the help of level

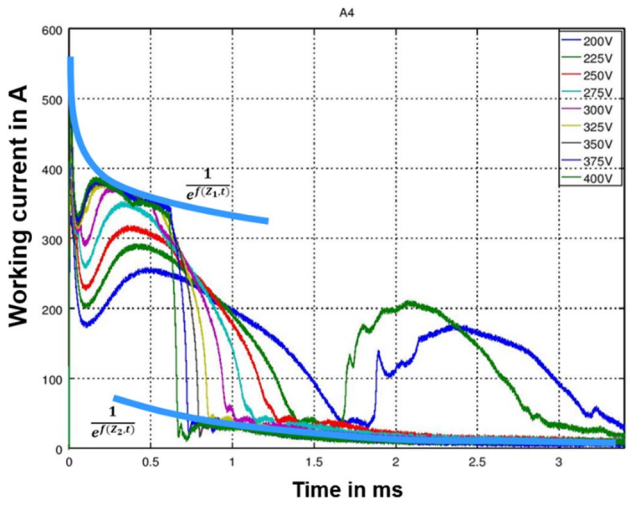


Fig. 7 Influence of the working voltage of the current curve in range of the initial phase [7]

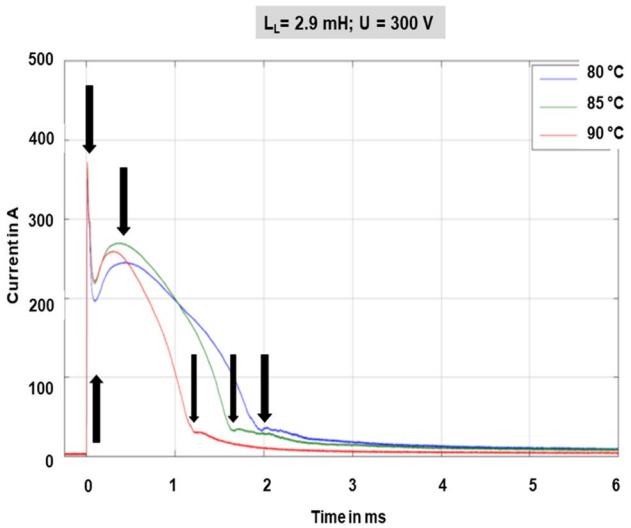


Fig. 8 Influence of electrolyte temperature of the PeP-Phases [7]

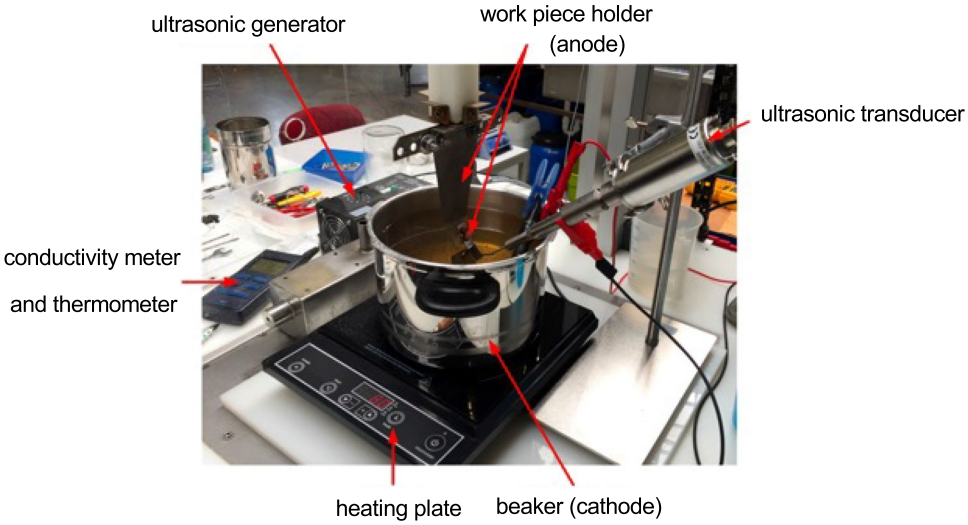


Fig. 9 PeP-setup for ultrasonic assisted procedure

sensors. The electrolyte circuit ensures a low flow of fresh electrolytes around the workpiece.

The existing electrolyte bath is replaced by a smaller basin. The actual experimental setup takes place in a basin with an electrolyte volume of approx. 5 L. The vessel is also used as a cathode and heated from below via a conventional induction heating plate. The Sonotrode is galvanically isolated from the rest of the system and a potential is set up corresponding to the operating voltage, which does not produce a significant EC effect. This must be observed in order to bring the Sonotrode to the same electrical potential as the cathode. The Sonotrode is then immersed in the electrolyte at a depth of approx. 2 cm. Alignment is carried out with the aid of a stand. The angular alignment of the Sonotrode is as perpendicular as possible to the workpiece, which is fixed at about 35 degrees to the mobile machine frame. The immersion depth of the workpieces can be adjusted via an electromagnetic contact on the mobile frame. The workpieces are immersed in the electrolyte bath to a depth of approx. 3 cm.

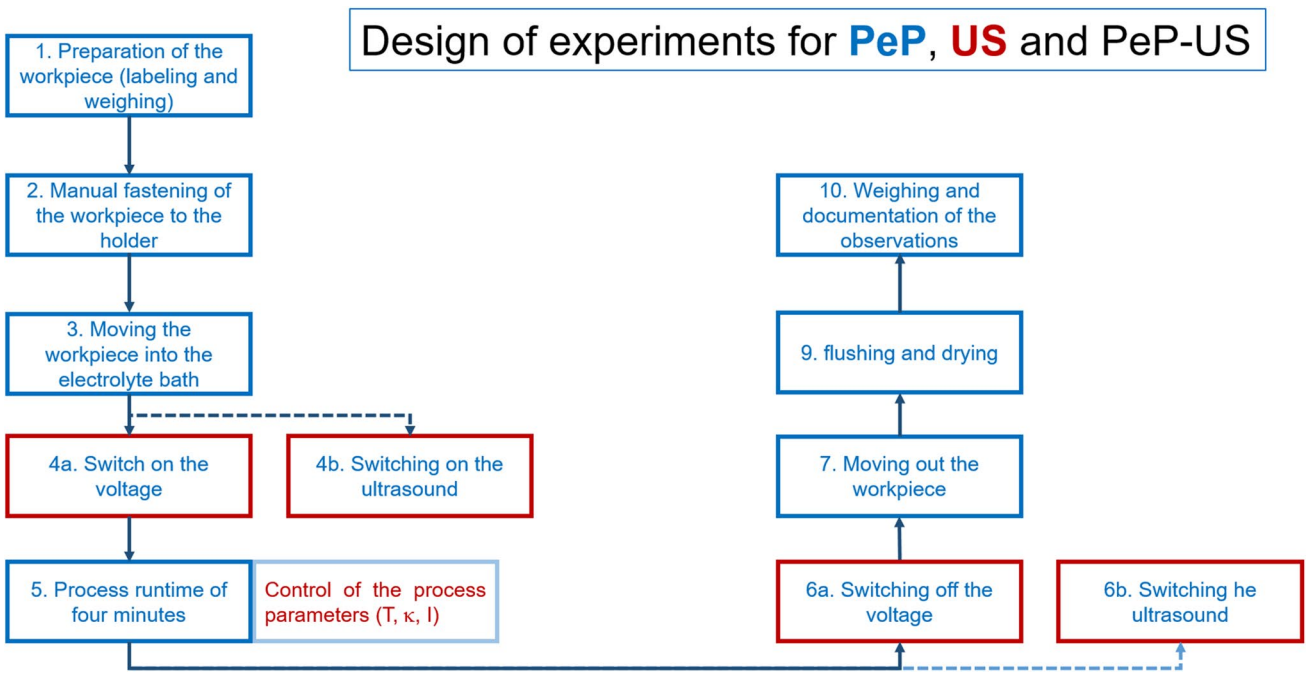


Fig. 10 Design of experiment for PeP, US and PeP-US

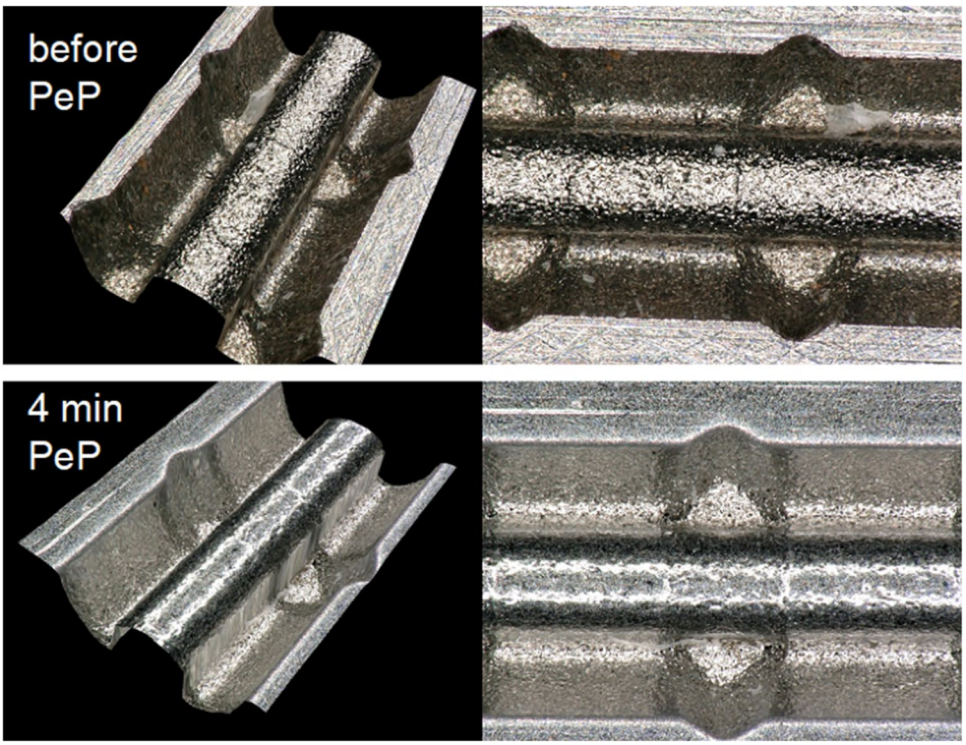


Fig. 11 Microscopic images of a forming tool before and after PeP

Test planning

50 sheets of 316 L/1.4404 material are prepared for the tests. These are pre-polished for three minutes to create a uniform surface for all tests. Pre-polishing is carried out in a material-specific electrolyte at a bath voltage of 370 V and an electrolyte conductivity of 120 mS/cm. The first experiments of Plasma electrolytic Polishing with ultrasound are to check if there is an effect of the ultrasonic field on the plasma. It will be investigated whether a variation in distance causes changes in the material removal behavior of the process and whether this has an effect on the roughness of the surface produced. A Sonotrode distance of 13 mm is chosen as the maximum and 2 mm was selected as the minimum distance. It is estimated that the thickness of the prevailing gas-vapor layer around the workpiece being processed is about 500 µm. In addition, during the variation of the distance, the amplitude of the US-Sonotrode is gradually changed from 20 to

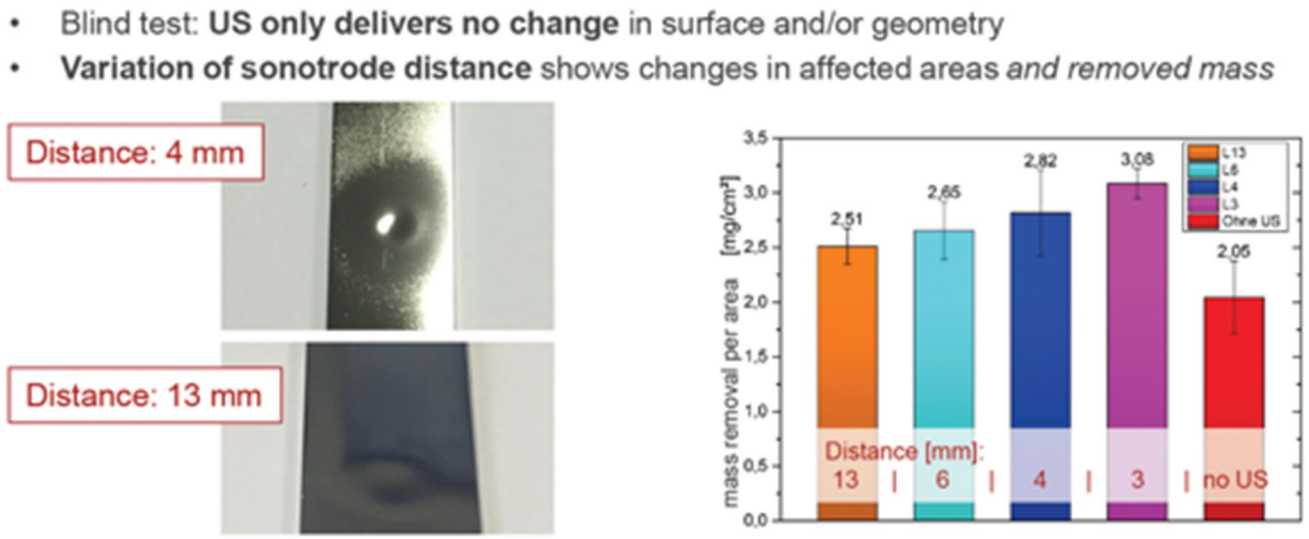
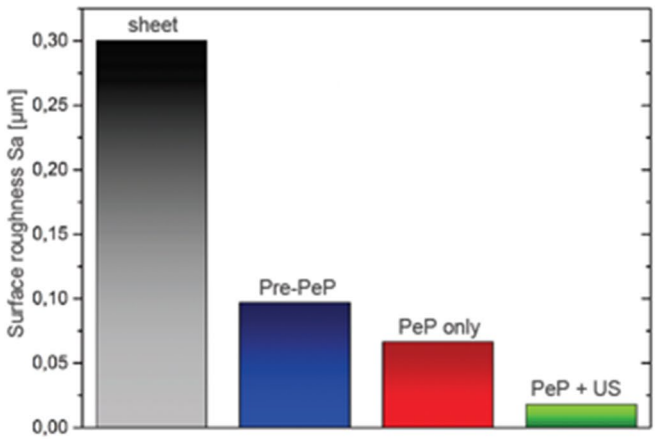


Fig. 12 Comparison of achieved results after ultrasonic-assisted PeP with a distance of 4 mm and 5 mm as well as removal mass in dependence of the Sonotrode distance



State	Sa [µm]
sheet metal	0.3
pre-PeP (3min)	0.097
PeP only	0.067
PeP + US	0.019

Fig. 13 Achieved surface roughness (Sa) depending on the PeP procedure

100% via the potentiometer located on the generator. For a more precise determination of the ablation behavior, all samples are weighed after pretreatment as well as after the experiment on the scale type Kern 572-31. From the difference, a possible correlation between mass loss and distance variation with amplitude variation should result.

Plasma-electrolytic Polishing (PeP) During the plasma polishing tests without ultrasound (Fig. 10a), the workpieces are processed under the previously mentioned conditions - without the high-intensity ultrasound being switched on. The US-Sonotrode is removed from the electrolyte bath during these experiments in order to avoid cathodic reactions on it. The known effects of the process, edge rounding or burr removal, the polishing effect, and gloss increase are to be made visible. The surface roughness achieved and the loss of mass are to be investigated as a matter of priority.

Ultrasonic machining (US) The distance from the Sonotrode to the workpiece is measured by means of a sliding gauge. The percentage of the amplitude is selected using the potentiometer on the generator. The approach of machining with high-intensity ultrasound is as shown in Fig. 10b.

PeP with assisted US (PeP-US) After the distance from the Sonotrode to the workpiece (DL) is set with the aid of a sliding gauge and the alignment is carried out at a 90 degree angle, the tests are run with ultrasonic support. The combination of plasma electrolytic polishing with high-intensity ultrasound is carried out as shown in Fig. 10a,b.

Results and discussion of the PeP of forming tools

PeP on surfaces of forming tools

By far the most frequently used material in metal forming is steel. Further materials are aluminum, copper and their alloys. The polishing of the metals is described in the literature and can be used on smooth flat surfaces [10–12]. On the other hand, undercuts, holes and mould pose challenges. This is very clear from a mould made from 1.2083 (Fig. 11, top), which has roughness peaks and impurities before polishing. Plasma electrolytic polishing removes the impurities and increases the surface gloss after just a few seconds. The recesses remain almost untouched. After a

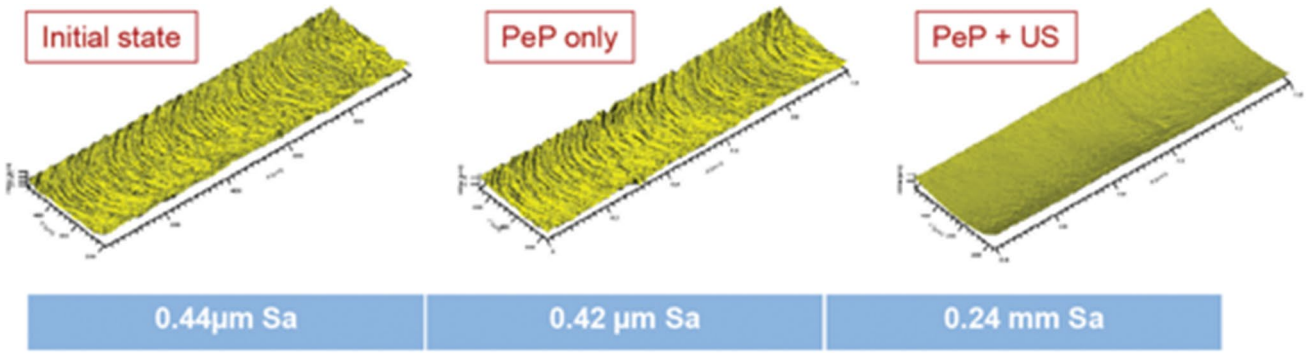


Fig. 14 Comparison of roughness at bottom area of recesses

rather long process time of 4 min for conventionally manufactured workpieces, the difference between the smooth, shiny central ridge and the rough recess is clearly visible (Fig. 11, bottom). Increasing the polishing time can remedy this, but is not an option due to the increasing edge rounding and a strong reduction in the dimensional accuracy of the component.

Possibilities for polishing recesses (trench structures)

In order to polish recesses, model systems were investigated which were subjected to directed ultrasound in addition to PeP. Figure 12 shows the mean values of the mass removal generated by Plasma electrolytic Polishing and PeP with ultrasonic support and their standard deviations. It can be seen that the mass removal of all PeP samples averages 2 mg/cm^2, while with ultrasonic support a removal of approx. 2,7 mg/cm^2 can be achieved over a period of four minutes. An increase in material removal of about 35% can be produced by using high-intensity ultrasonic in the processing of stainless steel. The increase in material removal depends, among other things, on the distance variation L of the Sonotrode to the workpiece (Fig. 11). Reducing the distance between the Sonotrode and the workpiece leads to increasing material removal. The average values show that at a distance of 13 mm a mass removal of approx. 2,5 mg/cm^2 can be achieved, while at a distance of only 3 mm it is already approx. 3,1 mg/cm^2. In contrast to pure PeP of this specimen geometry and an ablation of approx. 2 mg/cm^2, this is an increase of 55%. In conclusion, with regard to the material processed here with the electrolyte used the use of high-intensity ultrasound in the Plasma electrolytic Polishing process results in a significant increase in material removal.

Figure 13 shows a significant improvement in surface roughness. A reduction in the S_a value from 0,3 µm to 0,097 µm can already be seen after pretreatment. If this pretreatment is followed by 4 min of PeP, the surface roughness Sa can be reduced to 0,07 µm in the experimental setup. There is a significant reduction in the surface roughness Sa by processing with Plasma electrolytic Polishing and ultrasonic assistance. With the help of high-intensity ultrasound, a lowering of the surface roughness to as low as 0,019 µm is possible. With regard to the distances from 3 mm to 13 mm (L6 to L13), it should be noted that the surface roughness Sa decreases as the distance increases.

Since the trench samples are processed with a constant distance from Sonotrode to the workpiece, there are no comparisons to further distance variations. The amplitude is also fixed at 100% on the potentiometer of the generator and, according to the measurement, is approx. 140 µm peak-to-peak value. Three of the total six specimens are polished plasma electrolytically, while the others are processed in the electrolytic plasma with ultrasonic support. In the following, only the sample with a trench width of 0,5 mm is considered, since successful treatment in the bottom of the trench also suggests treatment in more accessible trench widths of 0,8 mm and 1,0 mm. Before processing, the untreated sample with the trench width of 0,5 mm is measured. Subsequently, the determined values are compared with the data of the processed samples. With regard to the geometry changes, statements can therefore be made about edge rounding and the formation of indentations. To determine the edge rounding, the specimen is set up at 45 degrees during the measurement so that a view of the trench flank and edge is possible. Due to the exposure to pure Plasma electrolytic Polishing, a clear edge rounding can be seen. The sickle-shaped milling structures are very clearly visible in the 3D image. On the other hand, the samples processed by Plasma electrolytic Polishing with high-intensity ultrasound are free of milling structures at the bottom of the trench. Thus, the existing surface structure in the trench with a width of 0,5 mm and a depth of 1 mm can be processed (Fig. 14).

Conclusion

The Plasma electrolytic Polishing process can be applied to a wide range of forming tools. The associated reduction in roughness peaks leads to advantageous properties.

By developing a phenomenological model in terms of accurate current measurement, the process initialization and polishing process can be optimized. Concise process parameters here are the electrolyte temperature and the operating voltage.

Another challenge is the polishing of trench structures. These can be polished uniformly by enhancing PeP with directed ultrasound, resulting in reduced edge rounding. Compared to conventional PeP, the removal rate is significantly increased and the roughness is reduced more quickly, resulting in shorter cycle times and higher productivity. In one example, the achievable roughness Sa is reduced from 67 nm (PeP) to 19 nm (PeP+US).

The possibility of smoothing bottom areas in recesses and cavities further increases application possibilities for PeP.

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Declarations

Conflict of interest The authors certify that they have NO affiliations with or involvement in any organization or entity with any.

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