



Principle, process, and application of metal plasma electrolytic polishing: a review

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Abstract

Plasma electrolytic polishing (PeP) is an innovative technology used to obtain metal surfaces with low roughness and a high gloss. Its advantages, which include high efficiency, no structural selectivity, and low pollution, have recently attracted much attention. PeP is widely used in aerospace, biomedical, precision instrumentation, and 3C electronics industries. This paper primarily aims to introduce basic principles of PeP technology from both the macro- and micro-mechanism viewpoints. Accordingly, the typical characteristics and phenomena of the polishing process are summarized. The primary control parameters which affect the surface quality and material removal rate are discussed in detail. These include treatment time, electrolyte, electrical source, and voltage. Furthermore, the electrolyte jet polishing methods applicable to parts with various geometries are also analyzed. Finally, the PeP surface treatment of selected difficult-to-finish materials is reviewed, followed by the authors' insights into the prospects of PeP technology. This review can serve as a suitable and effective guide for researchers to understand the PeP technology systematically.

Keywords Plasma electrolytic polishing (PeP) · Polishing principle · Key parameters · PeP application

1 Introduction

In the areas of aerospace, medical instruments, precision instrumentation, and 3C electronics, traditional polishing methods have been widely used to generate a low roughness and high gloss surface. However, with the rapid development of society and through innovation, traditional polishing technology aims to achieve higher polishing efficiency, higher polishing quality, and environmental protection. Traditional surface polishing techniques mainly include mechanical polishing, chemical polishing, and electrochemical polishing.

The mechanical polishing provides a way to obtain a smooth surface via plastic deformation through material surface cutting and grinding. Disadvantages include higher demand for manual labor, limited surface quality, and inability to process parts with complex geometries. On the other hand,

chemical polishing is a process that removes the workpiece material by controlled chemical dissolution by using a chemical solution. Similarly, electrochemical polishing also uses a chemical solution to dissolve the work material, but the process is performed under current. The metal workpiece is the anode, while the tool electrode is the cathode. Using direct current (DC), the workpiece as anode is dissolved into metallic ions and removed atom by atom. However, harmful gases are generated during both chemical and electrochemical polishing using strong acid or alkali chemical reagent. Additionally, harmful waste liquid is generated after polishing. Both the gases and liquid are damaging to workers' health and environmental protection [1–3].

The increasing number of complex structural parts and the growing environmental awareness make it is harder for traditional polishing methods to meet the current industrial polishing requirements. Therefore, in recent years, there is a rapid development of special polishing methods, mostly aiming to solve the problems mentioned above.

For abrasive jet polishing, abrasive particles are driven by the high-pressure liquid to impact the workpiece surface to achieve the micro-removal of the workpiece material [4]. Moreover, laser polishing is used to achieve exceptional surface finish levels through laser-material interactions,

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remodeling its topographic profile [5]. However, there are evident problems with both the abrasive jet and laser polishing methods. The former has low polishing efficiency for some of the hard and brittle materials, whereas the latter can cause surface ablation. Detailed characteristics of each polishing method are listed in Table 1.

Among the novel polishing methods, plasma electrolytic polishing (PeP) is an innovative technology characterized by high polishing efficiency and no pollution. Figure 1 presents the development of PeP technology, clearly showing its growth in popularity and advances. The PeP procedure was initiated by Duradzhi et al. in 1979 [7]. In 1986, Hans et al. [8] systematically proposed the PeP process parameters to improve the surface gloss of both single and multiphase alloys, such as brass, wrought alloys, and carbon-rich iron alloys. Stanishevsky et al. [9] developed the PeP method for metallic materials, including a variety of steels—stainless, tool, and low-carbon steels—aluminum, and copper and their alloys, which further popularized its application. In 1999, the apparatus and process for polishing metal surfaces using PeP technology were presented by Ryabkov [10]. The PeP method for smoothing pieces made of titanium and zirconium, including their alloys was introduced by Mirzoyev et al. [11]. Nevyantseva et al. [12] confirmed that PeP technology could also be used to remove coatings. Furthermore, the systematized PeP equipment was invented in 2008 [13], and a cobalt-chromium alloy was polished by PeP technology for the first time [14]. Subsequently, the technology was successfully applied to various metals, including magnesium alloys, amorphous alloys, gold, and platinum [15–17].

Theoretically, PeP technology can be used to polish any metal part structure. When compared to strong acid and caustic alkali solutions used in chemical and electrochemical polishing, the PeP technology uses a low-concentration salt solution electrolyte. Therefore, no harmful gases are generated. Furthermore, compared to mechanical polishing, abrasive jet polishing, and laser polishing, PeP technology has several distinct advantages. The advantages primarily include good surface quality, no mechanical stress, and no thermal

distortion/damage. Therefore, PeP can be widely applied for manufacturing machinery, medical instruments, in the aviation industry, meter manufacturing, 3C electronics, shipbuilding, food industry, and chemical industry, among others.

This review attempts to provide a more comprehensive understanding of the fundamental principles, typical characteristics and phenomena, and key parameters of plasma electrolytic polishing. Additionally, it also covers the polishing method using electrolyte jet for different shaped parts and applications in various difficult-to-finish materials.

2 The principle of PeP technology

Plasma electrolyte polishing is a composite reaction process that removes surface materials through plasma-physical and electrochemical reactions. As such, it is quite similar to common electropolishing. The standard PeP equipment is shown in Fig. 2. The setup includes a bath containing the polishing solution, in which the workpiece is immersed and connected as an anode. During the PeP process, both plasma and electrochemical reactions occur. The former includes the vapor gaseous envelope ionization, discharge bombardment, hydrothermal reactions, and metal dissolution by the metal-water reaction, while the latter includes oxide formation, metal dissolution, alkalization, hydrogen, and oxygen formation [18]. It should be pointed out that the physical reaction of plasma discharge bombardment is dominant and is the main cause of surface material removal. The voltage required for PeP is much larger compared to that of common electropolishing and is typically up to several hundred volts. Therefore, the material removal rate is high. Finally, it can be concluded that PeP is an efficient technology that can achieve metal surfaces with low roughness and high smoothness in a timely manner.

2.1 Macro-mechanism

The PeP macro model is described as a “power supply-electrolyzer-treated surface” system with lumped parameters

Table 1 Comparison of different polishing techniques [6]

Polishing techniques	Mechanical polishing	Chemical polishing	Electrochemical polishing	Abrasive jet polishing	Laser polishing	Plasma electrolytic polishing
Mechanism	Plastic deformation	Chemical corrosion	Electrochemical corrosion	Erosion and shear	Remelt regeneration	Plasma bombardment
Productivity	Low	Low	Average	Low	Low	High
Restrictions on geometry	Simple profile	Complex profile	Complex profile	Complex profile	Complex profile	Complex profile
Ecological level	Low	Low	Low	Medium	High	High
Energy consumption	Medium	Low	High	Medium	High	High
Qualification level of workers	High	Medium	Medium	Medium	Medium	Medium

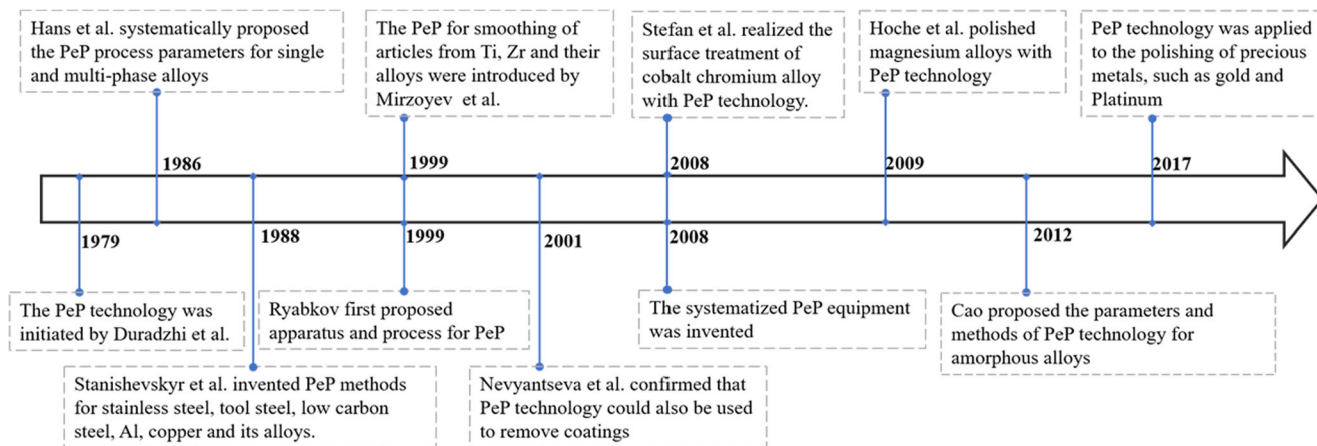


Fig. 1 The development process of PeP technology

[20]. The PeP layout schematic is shown in Fig. 3. Workpiece under DC voltage is immersed into a bath comprised of a specially formulated, temperature-controlled electrolyte solution and is connected to the plus pole of the DC power sources. Thus, the workpiece is the anode, while the cathode is connected to the minus pole of the DC power source. The polishing solution is electrolyzed at the start of the PeP. The electrolytic reaction occurs near the anode, including the oxygen evolution (Eq. (1)) and metal oxidation (Eq. (2)), which is expressed as follows:



where Me is the metal workpiece element.

Due to high voltage, an insulating gas layer is formed between the workpiece surface and the electrolyte, meaning that the electric circuit gets disconnected. When the voltage is high enough (between 200 and 400 V), the gas layer becomes ionized due to the high electric field within. The breakdown and discharge in the gas layer remove surface peaks, polishing the workpiece surface. Since the discharge removal rate is faster than oxidation, it can effectively remove surface peaks and achieve smoother surfaces [21].

2.2 Micro-mechanism

In-depth understanding of the PeP micro-mechanism can help us further analyze the macro-process. The streamer theory is suitable to explain the micro-mechanism of PeP [22]. The

Fig. 2 Typical arrangement of the PeP equipment [19]

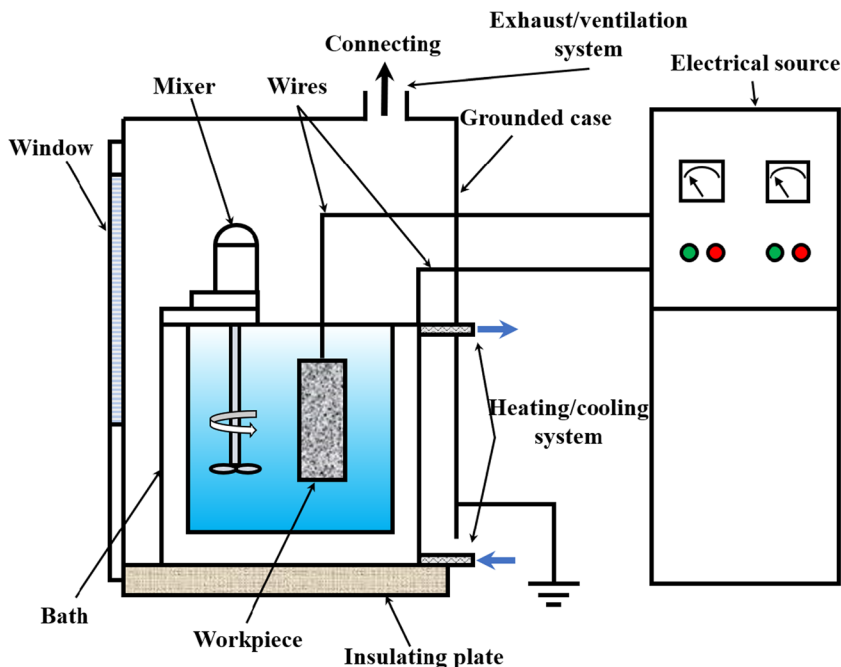
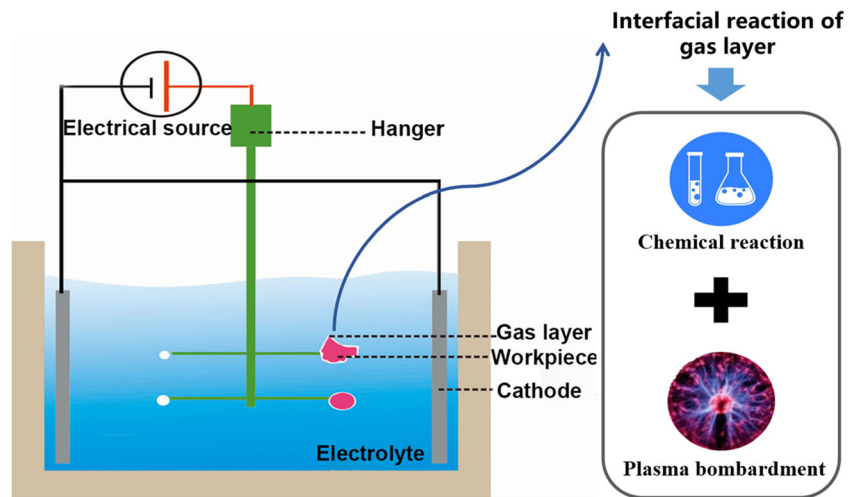


Fig. 3 Schematic diagram of PeP process

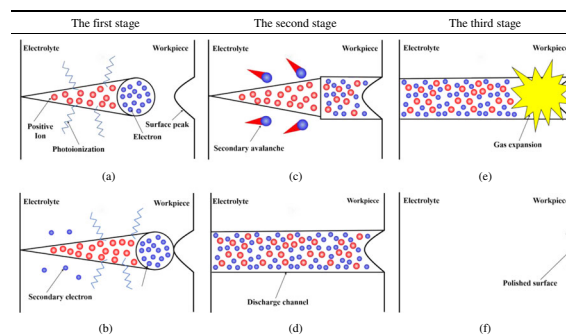


streamer theory of PeP is summarized in three stages [21, 22], as illustrated in Table 2. It shows the theoretical material removal process by plasma discharge during the PeP process.

- The first stage* is the avalanche formation and development. At first, the polishing solution is electrolyzed, accumulating a certain number of electrons and positive ions between the polishing solution and the workpiece. Since the electron mass is rather low, electrons move faster than the positive ions. After forming the gas layer, electrons form an avalanche head, while the positive ions remain in the back practically stationary as an avalanche tail (Table 2a). Furthermore, secondary electrons are formed as a result of photoionization, as shown in Table 2b.
- The second stage* is characterized by the formation of the plasma discharge channel. Electrons first reach the anode and form a primary plasma discharge channel with a part of positive ions. Simultaneously, secondary electrons are accelerated, forming secondary avalanches. These secondary avalanches are attracted by the primary plasma discharge channel, mainly due to the field distortion (Table 2c). When the process tends to stabilize, a complete plasma channel is formed (Table 2d).
- The third stage* includes gas explosion removal profile peak. Numerous collisions between the electrons and positive ions moving at high velocities produce a large amount of heat. Therefore, the plasma channel temperature increases, causing the gas to expand. The magnetic field of the electric current in the plasma channel restricts the gas expansion (magnetic compression). As shown in Table 2e, the result of the opposing processes (i.e., gas expansion and compression) is an explosion. After the gas explosion, the plasma channel collapses, removing the surface material (Table 2f).

The PeP micro-mechanism explains the process of reducing the workpiece surface roughness very well. There are three key factors in determining the rate of decrease of workpiece roughness during polishing—the rate of material removal (per discharge), the formation position of the discharge channel (in relation to the microscopic peak portion), and the discharge pit depth [23]. The PeP material removal rate is directly proportional to the anode current density [21]. The heat flux density on the workpiece surface increases with the increase in current density. This causes the workpiece surface layer to melt,

Table 2 Schematic drawing of micro-mechanism of PeP [21, 22]

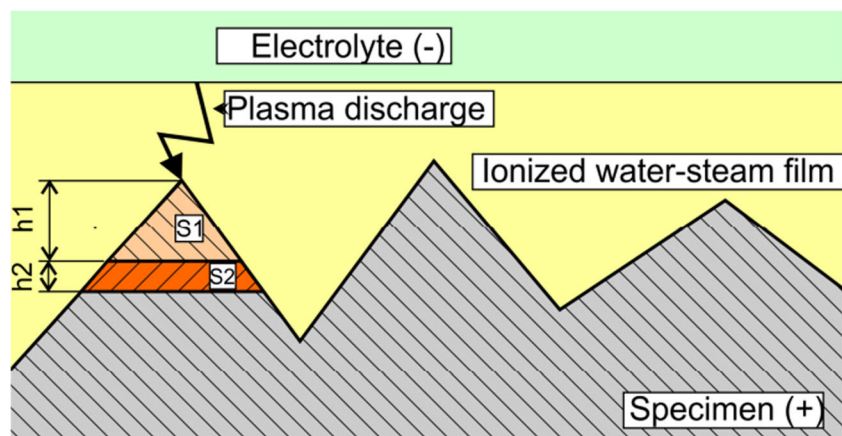


making it easier to remove [24]. During the polishing process, the current density in the cavities is lower than that at the peaks, resulting in faster removal of the material at peaks [25]. Vaňa et al. [26] reported that the material removal in PeP technology starts at the top of the surface peak, as plasma discharges melt away the workpiece surface. As shown in Fig. 4, each plasma discharge removes the same amount of material ($S1 = S2$). Thus, the thickness of removed layer $h2$ is much lower compared to the $h1$ layer thickness. Such behavior leads to rapid removal of the workpiece surface peaks, achieving a smooth surface effect.

2.3 Current-voltage characteristic

Typical current-voltage characteristics of the PeP anode process [27] are shown in Fig. 5. The curve shows several sections which correspond to various polishing process voltages. The section of current-voltage characteristics between points A and B represents the common electropolishing process. The A–B section is described by Ohm's law and Faraday's law, and a positive correlation is found between current and voltage. When the voltage is at point B, a film consisting of vapor and gas is periodically formed around the active electrode. However, the vapor-gas film oscillates on the active electrode until the voltage value increases to point C. The B–C section is described as the unstable PeP process. Since point C, the gas layer of the anode is stable, but the luminescence phenomenon is still not obvious. Until point D spark discharges create the glow, the emergence and disappearance of gas layer are accompanied by crash and noise. Thereby, the C–D section and the following section of the current-voltage characteristic are the stable PeP processes. Among them, the C–D section is the heating zone, and the anode temperature in the area after point D gradually decreases. This area is described as the electrohydrodynamic process mode, which is the only one used for PeP. Furthermore, in the C–D section, the workpiece polishing generally takes place at voltages between 200 and 350 V, with a current density between 0.2 and 0.5 A/cm².

Fig. 4 Surface profile of the treated specimen according to Vaňa et al. [26]



It should be noted that the heating zone only exists under a specific set of circumstances. Point C position depends on the electrolyte composition, concentration, and temperature [28]. Additionally, the current density has a strong negative correlation to the temperature; the current density decreases as the temperature increases [29].

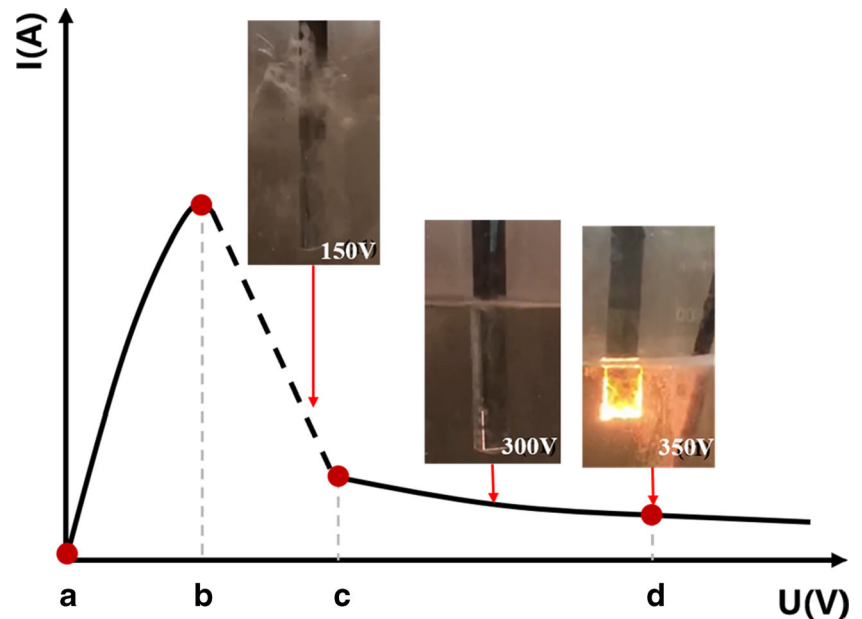
2.4 The typical phenomena: gas layer and plasma discharge

In the polishing process, a gas layer is formed between the anode and the electrolyte due to a high-voltage value. The gas layer consists of vapor and other gases, which is nonconductive and separates the metal surface from the electrolyte. Kellogg [30] indicated that the gas layer surrounding the anode during the aqueous anode effect is maintained by the electrolyte vaporization. The gas layer is also known as the gaseous vapor envelope (VGE) since its fundamental component is water vapor. Based on the simulation and experimental results, Danilov et al. [31] concluded that the most significant voltage drop in PeP occurs in the gas layer.

The voltage was found to have an important influence on the gas layer formation; the energy gain on the workpiece surface increases with the voltage. Moreover, the energy gain on the workpiece surface per time unit plays an important role in the gas layer thickness—the larger the energy gain, the thicker the gas layer. It should also be added that a thicker gas layer is more stable [32]. The high electrolyte temperature is also critical to the gas layer formation. The continuous gas layer surrounding the sample does not appear at low-temperature electrolytes [29]. Duradji and Kaputkin [33] suggested that the layer thickness should not be lower than 0.05 mm for all electrolytic solutions. The generation of gas bubbles on both the anode and cathode is observed—O₂ at the anode and H₂ at the cathode [34]. It should be pointed out that the remaining gas in the layer is predominantly O₂.

Plasma discharges occur in the gas layer during the polishing process, resulting in the high-temperature energy

Fig. 5 Typical current-voltage characteristic of the PeP anodic process [27]: A–B, the common electropolishing process; B–C, the unstable plasma electrolyte polishing process; C–D and D–, the stable plasma electrolyte polishing process



being released, removing the excessive workpiece material. The gas layer temperature can locally reach as high as 2000 °C [35]. A luminous glow can be seen on the plasma discharge gas layer. The luminous glow color varies depending on the type of metal ions present in the electrolyte. For example, an orange-colored glow is regularly seen in a solution containing sodium ions, while a blue-colored one is seen when using a solution consisting of Zn ions [35]. The presence of the gas layer is essential for sustaining anodic dissolution on the workpiece surface, providing both the cleaning and polishing effects [36]. Figure 6 shows a schematic diagram covering the gas layer evolution stages between the electrolyte and the working electrode [20, 37].

3 Key parameters affecting the PeP process

The factors related to plasma electrolytic polishing include electrolyte, electrical source, process parameters, pretreatment, posttreatment, cathode, hanger, and workpiece. The

surface quality and material removal rate are affected by a number of PeP parameters, as shown in Fig. 7. Since many PeP process parameters are complex and should be optimized, it is difficult to find the polishing parameters suitable for each metal. Researchers generally select key parameters to optimize the other process parameters. Such parameters have a great impact on the removal rate and surface roughness, as well as treatment time, electrolyte, electrical source, and voltage.

3.1 Treatment time

The treatment time is an important parameter in the plasma electrolyte polishing process. Rajput et al. [38] reported the experimental details for confirming the relationship between the current and decrease in surface roughness with increase in treatment time; the voltage was held constant. Figure 8 shows the surface image of the copper material after PeP with $t_{\text{PeP}} = 15$ s and $t_{\text{PeP}} = 120$ s. It is evident that longer treatment time can result in a smoother surface [39]. Dobrynin [40] studied

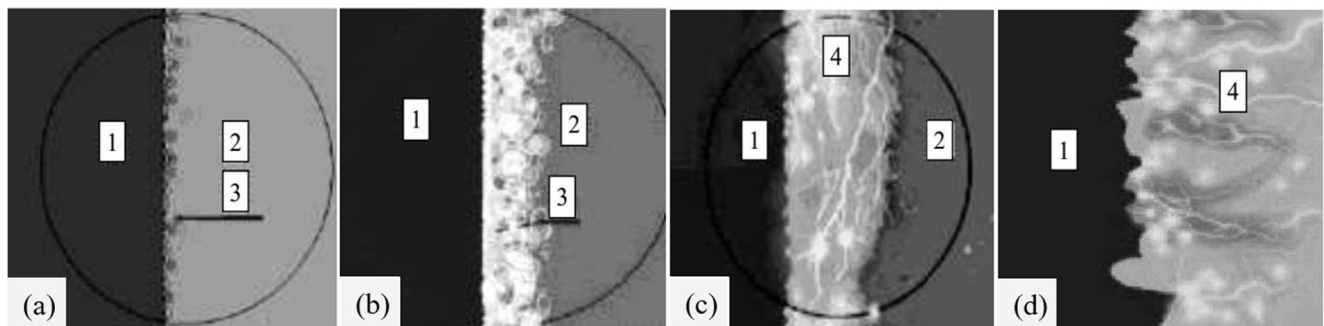


Fig. 6 Gas layer evolution stages: **a** oxygen evolution, **b** gas layer bubble boiling, **c** micro-discharges in the gas layer, **d** surface structuring produced by micro-discharge treatment; 1, working electrode; 2, electrolyte; 3, oxygen and vapor bubbles; 4, micro-discharges [20, 37]

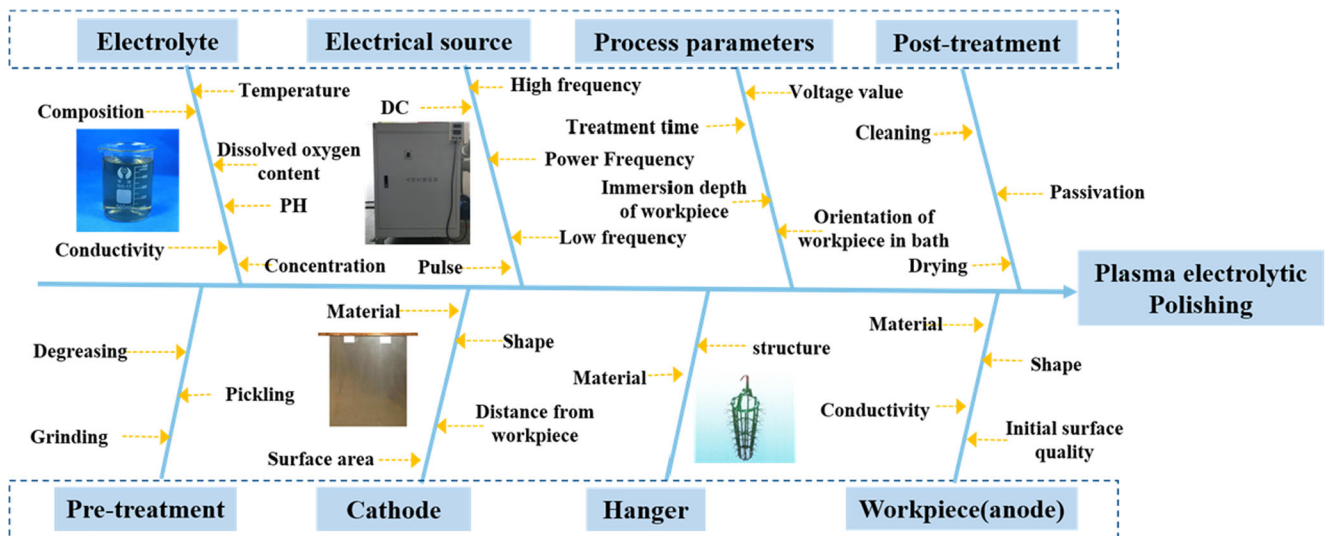


Fig. 7 Effect factors of surface quality and material removal

the effect of PeP on the surface roughness of samples made of titanium alloys VT6 and VT8M-1. When the polishing time reaches a specific time node, the sample surface roughness remains unchanged. Furthermore, Podhorský et al. [41] investigated the possibilities of using the PeP technology to pretreat the low-carbon steel surface before galvanic chrome plating. As shown in Fig. 9, the authors observed that the resulting surface roughness rapidly decreased in a brief time period. However, with long polishing times, the surface roughness was found to increase slightly. In a later study, Vana et al. [42] further studied this phenomenon. They evaluated the change in surface gloss level and roughness of the austenitic stainless steel surfaces after PeP through time. They found that a very short polishing time has a radical effect on the increase in the surface gloss level. However, the secondary surface relief is created by increasing the treatment time and decreasing the surface gloss level. Similar to the gloss level change, the surface roughness increases with the polishing time.

As shown above, there is a limit to workpiece surface roughness that can be achieved by using PeP. The effective polishing time, described as the period between the polish start and reaching the stable surface roughness, is critical to achieve the minimum surface roughness. In addition, minimum achievable roughness is also associated with the initial

workpiece roughness. The relationship between the workpiece surface roughness parameter Ra and treatment time t can be described as [43]:

$$Ra = A \cdot \exp(-kt) + C \tag{3}$$

where A is the maximum decrease in roughness, k is the coefficient accounting for the polishing conditions and the physical workpiece properties, and C is the minimum achievable roughness.

As described in Section 2, PeP is similar to the commonly used electropolishing process. The largest differences are found in the electrolyte type and the voltage level. When compared with electropolishing, for given current densities, the use of PeP can realize both lower surface roughness and higher gloss in a shorter polishing time. To achieve comparable results by using electropolishing, process time would be eight times higher [39].

3.2 Electrolyte

The electrolyte composition, concentration, and temperature have a significant impact on the machining efficiency and surface roughness. The selection of the PeP electrolyte is

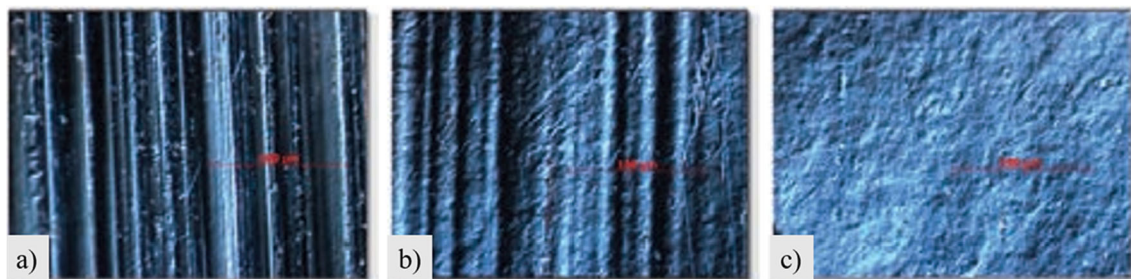


Fig. 8 Copper material surfaces: a untreated, b after 15 s PeP, and c after 120 s PeP [39]

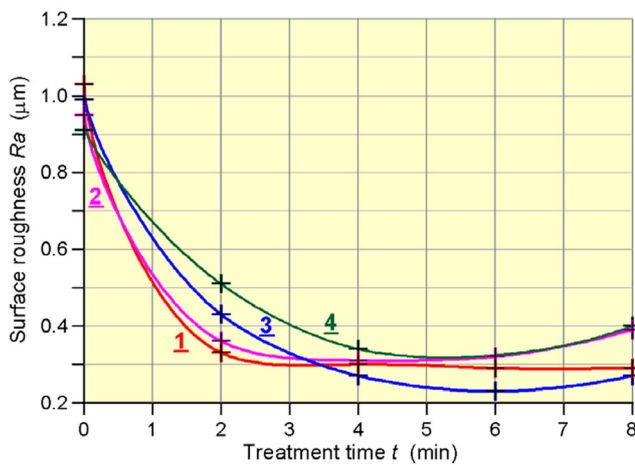


Fig. 9 Relationship between surface roughness of the specimens and the treatment time (the serial numbers 1, 2, 3, and 4 in the figure are the sample numbers) [41]

highly dependent on the pre-polished metals and alloys. For example, the low-concentration salt solution with ammonium sulfate as the main component is used for polishing steels. The polishing performance can be further improved by including additives to the electrolyte. Additives such as surfactant and glycerol [44] can significantly affect the electrolyte surface tension, kinematic viscosity, and conductivity properties. The change in electrolyte concentration will also affect the polishing process. Kashapov [45] indicated that increasing the electrolyte concentration will affect both the anodic dissolution and the occurrence of anodic micro-discharges. Wang et al. [24] found that stainless steel removal rates increase with the increase in ammonium sulfate solution concentration up to 6% and then decrease when the concentration is more than 6%, as shown in Fig. 10. Such behavior occurs since increasing concentration can improve the electrolytes' electrical conductivity, electric field strength, and collision ionization coefficient. In the collision, electrons bombard the workpiece surface, increasing the removal rates. However, too high electrolyte concentration will negatively affect the polishing reaction, thereby reducing the removal rate.

The electrolyte temperature is another serious concern during the polishing process. A high-quality workpiece surface can be achieved only in the limited range of electrolyte temperatures. As the temperature increases, the evaporation rate of water within the electrolyte also increases. This makes the gas layer more stable, which results in improved polishing surface quality. However, if the temperature is too high, it can destroy the chemical components of the electrolyte [31]. Wang et al. [43] compared the effects of temperature, electrolyte concentration, and diving depth on the surface roughness. They found that temperature is the most important factor when considering surface roughness. Mihai et al. [29] observed a strong negative correlation between the current drop of steel AISI 304 and increase in the electrolyte temperature. The

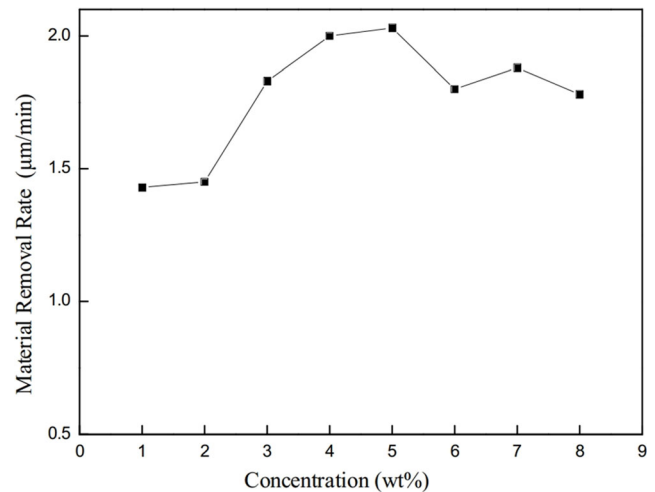


Fig. 10 Material removal rate at different concentrations [24]

physical and chemical properties of the electrolyte solution change with the increase in temperature. Additionally, the pH and dissolved electrolyte oxygen also affect the polishing efficiency and its effect. Valiev et al. [46] pointed out that the electrolyte pH not only affects the anode current density but also the workpiece surface roughness. To conclude, the electrolyte composition has the most significant influence on PeP for different metals.

3.3 Electrical source and voltage

Electrical source and voltage parameters are critical to surface quality and removal rates. PeP technology uses a unique high-power electrical processing source with either regular or pulsed DC sources. The latter can control the process interruption and arc duration. Unlike regular DC sources, the pulse sources rely on the pulse effect to accelerate electrolyte flow and renewal during the polishing process. Thus, the workpiece finish and polishing are achieved with higher efficiency and better surface performance [16].

On the other hand, the most significant PeP limitation is high energy consumption. In order to reduce energy consumption, a novel polishing mode was developed—described as two-stage polishing. The voltage is called step DC voltage. The first stage is polished at a higher voltage, while the second stage is processed at a lower voltage [47]. Compared to DC constant voltage polishing, the proposed two-stage polishing mode can reduce polishing time and improve the polished effect. The schematic illustration of the voltage waveform is shown in Fig. 11. Moreover, researchers have found that the source frequency also has a notable influence on the polishing effect. A study by Yerokhin et al. [48] confirmed that the PeP process is more effective at a higher frequency source. In addition, the process energy source determines the maximum polishing area for one loading.

Selecting a very low-voltage value has a negative impact on the PeP process since VGE cannot be formed under the low-voltage treatment conditions. Parfenov et al. [36] reported the effects of VGE on the electric field distribution and surface layer removal during stainless steel PeP. The authors carried out both theoretical and experimental studies. Low-voltage treatments without VGE may cause the workpiece to passivate, with resulting oxide layers blocking the surface polishing (Fig. 12b). However, VGE formation during the high-voltage PeP processing promotes anodic metal dissolution and provides a smooth surface (Fig. 12c). Wang et al. [32] indicated that the voltage has an important role in the surface roughness value and the material removal rate. If the voltage is either too large or too small, the minimum achievable surface roughness value will increase. On the other hand, rising voltage increases the amount of heat released near the anode, making the gas layer thicker and more stable and thus decreasing the current. The material removal rate decreases while the roughness decrease rate becomes slower. Due to the short circuit at a low voltage, the smallest achievable surface roughness value increases.

3.4 Other effects

Other factors that influence the plasma electrolyte polishing process include metal surface pretreatment, posttreatment, workpiece immersion depth, workpiece orientation (in the bath), cathode material, hanger, electrode spacing, and bath age, among others.

The pretreatment is an essential precondition to achieve the highest surface quality [50]. Before PeP, metal parts are mechanically prepared. The metal surface is generally covered by an oxide layer (or any other dirt), thus requiring the pretreatment process for the workpieces to be polished. The examples of pretreatment processes are surface cleaning and mechanical abrasive grinding. Pretreatment will reduce both the PeP polishing process time and increase resulting surface quality in case of burrs and other defects found on the end product. The posttreatment process is also essential to avoid chemical residues on the workpiece surface after polishing. The workpiece immersion depth indicates the solution pressure on the

workpiece surface. The deeper the workpiece immersion depth, the greater the workpiece surface pressure, which can adversely affect the formation of a stable gas layer on the workpiece surface. To ensure the necessary current density for plasma formation at the workpiece (anode) surface, the cathode surface area must be larger than the workpiece.

The key factors have a significant impact on metal treatment surface quality. Basic PeP quality indices, which include the surface roughness and gloss, depend on the principal process parameters—treatment time, composition, concentration, electrolyte temperature, electrical source, and voltage on the electrodes. Depending on the metal, the most suitable polishing electrolyte must be developed. Additionally, high temperature is an important factor when forming a stable gas layer and ensuring the polishing quality. However, the electrolyte temperature should not be too high as it will destroy the electrolyte composition. High voltage is beneficial to the gas layer formation, allowing the workpiece to achieve a higher polished surface quality.

4 Polishing method using electrolyte jet for various shaped parts

Plasma electrolyte polishing successfully enables metal product finishing. However, there are a number of unresolved technical issues restricting its application. Due to the working bath size limitation, PeP equipment cannot process large parts, including large flat workpieces, large cylindrical workpieces, and long-length workpieces. Moreover, since the electrolyte does not flow in the working bath, it cannot reach workpieces with deep holes, making it difficult to polish such surfaces effectively.

For such cases, electrolyte jet PeP is recommended. PeP with electrolyte jet is a method that uses a pressure pump to convert the electrolyte into a liquid using pressure. The pressure propels the electrolyte to the nozzle to form a jet to spray the workpiece surface and polish it. Compared with the common immersion polishing method, electrolyte jet polishing is not limited by the bath size and can process parts of any shape and size (Fig. 13).

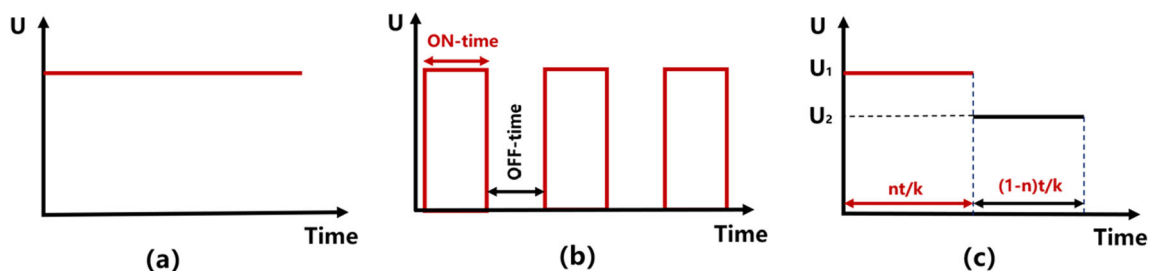


Fig. 11 Schematic illustration of voltage waveform: **a** DC constant voltage, **b** pulse DC voltage, **c** step DC voltage [47, 49]

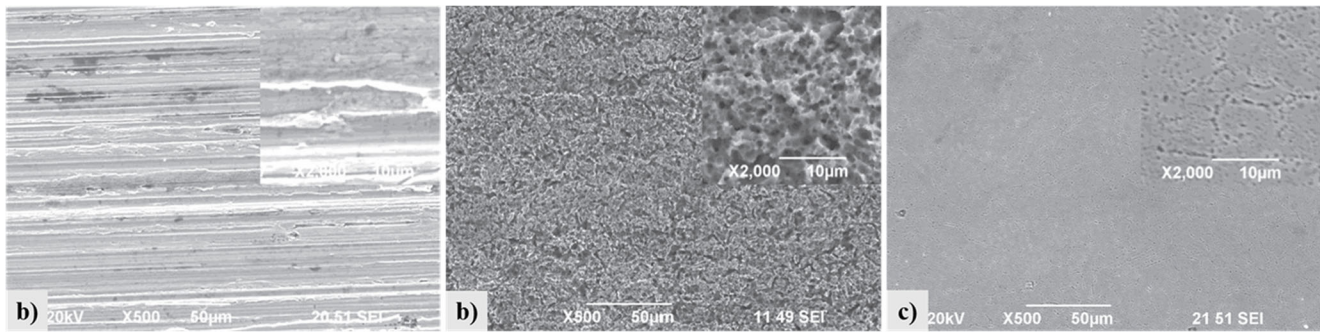


Fig. 12 Surface plane SEM images of stainless steel before treatment (a), after PeP for 15 min at 9 V (b), and after PeP for 15 min at 250 V (c) [36]

4.1 Large flat workpiece

Large flat workpieces are parts whose dimensions in the horizontal and vertical directions exceed the bath size, for example, large sheet metal parts. As shown in Table 3a, the bath (cathode) is connected to the negative side of a DC source, while the positive DC source side is attached to the workpiece (anode). The workpiece is driven by a movable mechanism to achieve translation in two directions. In order to close the electrolytic cell, the electrolyte is sprayed through the nozzle by the pump, forming the jet and covering the workpiece surface. When the DC source is turned on, the workpiece surface material is removed.

4.2 Large cylindrical workpiece

The term large cylindrical workpiece refers to a rotating body part whose diameter exceeds the bath size (i.e., aeroengine or cylindrical thin-walled parts). The polishing method for a large cylindrical workpiece with electrolyte jet is shown in Table 3b. The cylindrical workpiece is rotated around the central axis. A pump feeds the electrolyte from the bath through a flexible hose to the workpiece surface, closing the electrolytic circuit. The slow-speed reversible motor drives the spindle to move the nozzle along the central workpiece axis, allowing the entire workpiece to be polished.

4.3 Long-length workpiece

Long-length workpieces include tapes, tubes, and wires. The device setup for PeP of such workpieces is shown in Table 3c. A slow-speed reversible motor is connected to the long-length workpiece, driving it along the axial direction. A pump conveys the electrolyte from the bath, through a flexible hose, to the storage tank. The nozzle is connected to the drain at the bottom of the storage tank. Under the action of gravity, the electrolyte within the storage tank is sprayed through the nozzle to cover the workpiece surface, forming a closed loop required for processing.

4.4 Workpiece with deep holes or cavities

As implied by their name, workpieces with deep holes or cavities have holes or cavities of much larger depth than their cross-sectional size (i.e., cylinder hole, axial shaft oil hole, hollow main shaft hole, and hydraulic valve hole). The installation diagram of the PeP workpiece with deep holes or cavities using an electrolyte jet is shown in Table 3d. The workpiece is immersed in a bath filled with electrolyte. The hoisting mechanism is connected to the workpiece, allowing it to achieve vertical movement. The pump blades rotate, accelerating the electrolyte and thus filling inner surfaces of the

Fig. 13 Schematic diagram of immersion (left) and electrolyte jet (right) polishing methods [51]

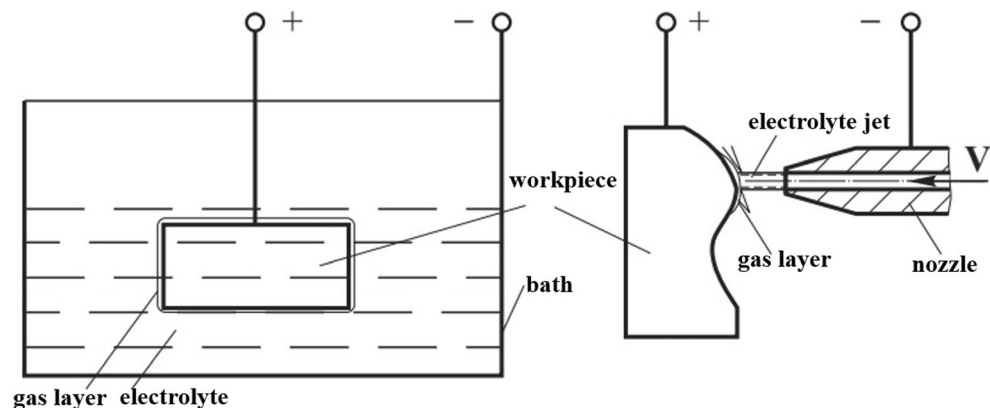
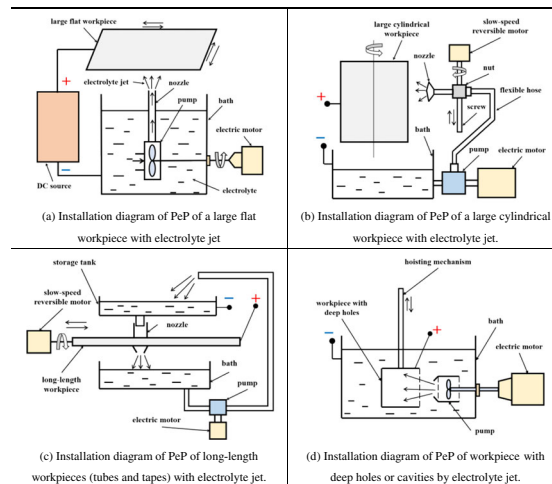


Table 3 Processing with jet electrolyte flows [52]

workpiece cavity. When the DC source is turned on, the inner workpiece surface with a cavity is effectively polished.

The electrolyte jet PeP is also a recommended choice for polishing geometrically complex workpieces. Abyaz et al. [53] demonstrated its applicability to polishing complex components produced by selective laser melting. In recent years, industrial robots are widely used in industrial production due to their flexibility, affordable price, and mechanical reconfigurability [54]. Wang et al. [55] proposed an industrial robot with a free electrolyte jet as the basis for a novel PeP technology automation. Such a solution is effective and economical for surface treatment of both geometrically complex and large-size workpieces.

The electrolyte jet PeP can be used to polish large flat workpieces, large cylindrical workpieces, long workpieces, workpieces with deep holes or cavities, and other parts of complex geometry. The electrolyte jet pressure needs to be controlled in a suitable range (0.02 to 0.05 MPa). A very low pressure will prevent the electrolyte from entering the inner surface, meaning that the inner surface cannot be polished. On the other hand, a very high pressure will affect the gas layer formation, making the process unstable [53].

5 Surface treatment of different difficult-to-finish materials

Currently, scholars have successfully polished steel, aluminum, copper, titanium, and their alloys, as well as several other metals and surface coatings. Additionally, PeP can be used to process some of the additive manufactured metals [56, 57]. A summary of the primary PeP process parameters (electrolyte, voltage, initial temperature, and roughness) used to polish various metals is shown in Table 4.

5.1 Stainless steel

Several studies have been carried out on stainless steel PeP, focused on the process parameter optimization to achieve the minimum surface roughness and high gloss. The polishing solution for such process is generally an ammonium sulfate electrolyte with a concentration of 3% to 5%, while also requiring the higher polishing voltage. Podhorský and Bajčičák [34] found that a higher surface gloss level is achieved at lower electrolyte concentrations. However, the ammonium sulfate electrolyte concentration cannot be too low, as it could reduce the process stability. After analyzing experimental results, Mihal et al. [29] determined that a low concentration of ammonium sulfate solution leads to the highest polishing quality.

The optimum parameters for AISI 304 steel in an ammonium sulfate solution (mass fraction of 3%) are processing time below 390 s and temperature above 60 °C. Stainless steel was also polished by Wang et al. [43], and the optimal processing parameters were proposed. The ideal ammonium sulfate concentration range needs to be as low as 4% to 5%, with the temperature of 80 °C and 5 mm diving depth. Volenko et al. [73] studied the influence of electrolyte composition and multistage polishing on the austenitic stainless steel process technology parameters and surface roughness. The sulfuric acid concentration range was between 4 and 5%, with the addition of 0.05% to 0.45% hydrogen chloride to reduce the working electrolyte temperature. When compared to traditional polishing methods, the multistage polishing decreases the surface roughness by 20% to 25%. In addition to low electrolyte concentration, the surface quality can also be improved by applying high voltage. As shown in Fig. 14, Cornelsen [74, 75] found that the initial inner pipe surface with irregularities and fractures can be processed into a smooth surface. The Sa

Table 4 Summary of major PeP process parameters for various metals

Metallic material	Electrolyte ratio (wt%)	Initial temperature range (°C)	Voltage range (V)	Roughness (μm)	Literature reference (No. 1)
Stainless steel	2–5% $(\text{NH}_4)_2\text{SO}_4$	80–95	250–400	R_a 0.573–0.060	Wang [32, 43], Ding [58]
Stainless steel	2–6% $(\text{NH}_4)_2\text{SO}_4$	40–80	240–320	R_a 0.65–0.12	Stanishevsky [9]
Low-carbon steel	0.5–8% NH_4Cl	81–95	240–380	R_a 1.20–0.21	Stanishevsky [9]
Alloy steel	3–8% $(\text{NH}_4)_2\text{SO}_4$	70–85	260–310	/	Dyblenko [59]
Structural alloy steel	3% NH_4Cl , 1% $(\text{NH}_4)_2\text{SO}_4$, 0.5% Trilon B	90	270	R_a 1.5–0.4	Abylaz [60]
Carbon steel	3% NH_4Cl , added glycerol or oxalic acid	78–82	275–300	/	Belkin [61]
Brass	0.5–8% aluminum potassium sulfate	40–90	220–400	R_a 0.60–0.05	Stanishevsky [9]
Copper alloy	NH_4Cl , NH_4F , $\text{C}_6\text{H}_5\text{O}_7$ $(\text{NH}_4)_3$	60–90	250–340	/	Dyblenko [62]
Aluminum alloy	2–3% KCl , 3–4% FeCl_2 , 0.1–0.2% HCl	/	270–290	R_a 0.12–0.04	Rakhcheev [63]
Aluminum alloy	4–5% KNO_3 , 2–3% $\text{C}_6\text{H}_8\text{O}_7$, 0.5–1% $\text{C}_3\text{H}_8\text{O}_3$	/	280–320	R_a 1.2–0.2	Zakharov [51]
Aluminum	0.5–3% FeCl_3	70–90	260–400V	R_a 1.03–0.30	Stanishevsky [9]
Aluminum	10% NH_4Cl , 4% KCl , 3% $\text{H}_2\text{C}_2\text{O}_4$	60–80	280–360	R_a 0.015	Duradji [64]
Titanium or titanium alloy	1.5–3% NH_4Cl , 1.25–2.75% NH_4F	80–95	280–320	R_a 0.12	Lingath [65]
Titanium alloy	2–7% NH_4F and KF , 0.3–0.8% TiF_4	70–90	320–340	R_a 0.50–0.05	Damir [66]
Titanium alloy	2% Na_2SiF_6	50–60	100–400	R_a 0.08	Smyslov [67]
Ti /Nb	4% NH_4F	75–95	260–300	R_a 0.1/ R_a 0.2	Aliakseyeu [68]
Ti-6Al-4V	4–6% hydroxylamine hydrochloride and 0.7–0.8% NaF or KF	85–95	260–280	R_a 0.004	Smyslova [69]
Ti/Zr and their alloys	Borhydrofluoric, fluorosilicic, hexafluorotitanium, or hydrofluoric acids	80–85	200–400	/	Mirzoyev [11]
Iron chrome alloy	NH_4Cl	60–90	270–290	R_a 0.45–0.02	Mingazhev [70]
Cobalt-chrome alloy	$(\text{NH}_4)_2\text{SO}_4$ or NH_4HSO_4	>80	300–380	/	Stefan [14]
Gold	4% NH_4NO_3 and NH_4Cl (1:3)	50–60	100	R_a 0.221–0.012	Polak [17]
Platinum	4% NH_4NO_3 and NH_4Cl (1:3)	60	300	R_a 0.03	Polak [17]
Magnesium alloy	0.5% CH_3COONa , 0.15% $(\text{HOCH}_2\text{CH}_2)_3\text{N}$, 0.05% $\text{C}_6\text{H}_{11}\text{NaO}_7$, 0.01% $\text{C}_6\text{H}_8\text{O}_7$	65–95	340, 10kHz, duty cycle 90%	R_a 1.00	Zhang [71]
Zr-based amorphous alloy	$(\text{NH}_4)_2\text{SO}_4$, NH_4HF_2	50–100	100–380	R_a 0.200–0.072	Wang [72]
Zr-based amorphous alloy	2% Na_2SO_4 , 0.2% $\text{H}_8\text{MoN}_2\text{O}_4$, 0.2% NH_4HF_2	85	300, 15kHz, duty cycle 15%	R_a 0.04	Cao [16]

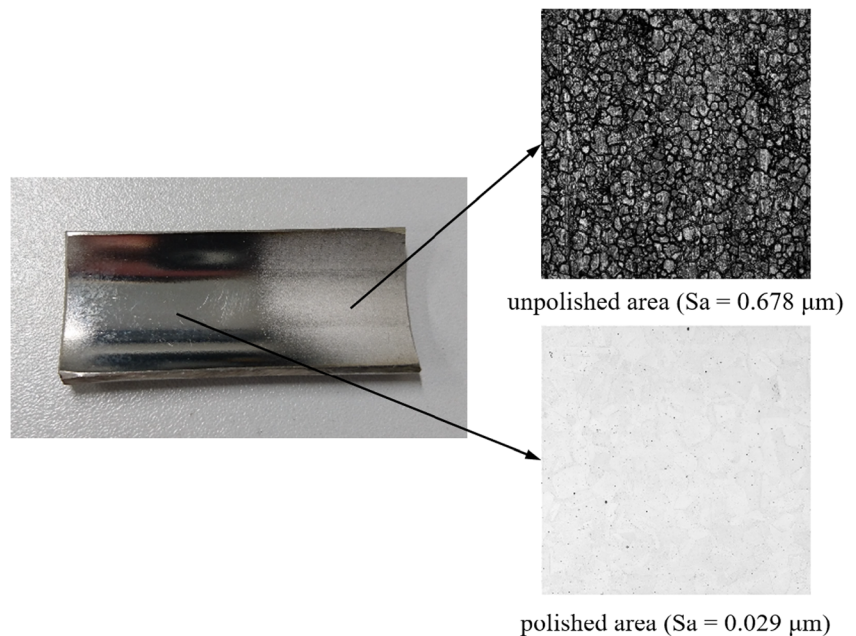
surface roughness reduced from 0.678 to 0.029 μm at the voltage of 320 V. Finally, Starovoytov et al. [76] stated that PeP reduces the stainless steel surface roughness several times without affecting the original modified layer.

5.2 Alloy steel

The majority of the literature pointed out that PeP technology can reduce the alloy steel surface roughness while

also having a beneficial effect on both the surface wear and corrosion resistance. The electrolyte used for alloyed steels is a salt solution with either ammonium sulfate or ammonium chloride as the main component. Abylaz et al. [60] confirmed that the PeP technology is feasible to improve the surface quality of 38KH2N2MA steel after electrical discharge machining (EDM). The workpiece surface following the EDM was characterized by numerous stacked holes (Fig. 15a), which were eliminated after

Fig. 14 The top view of an unpolished and a polished tube inner surface at the voltage of 320 V [74]



polishing. Cheng et al. [77] reported that a nanocrystalline surface layer with a thickness of approximately 2 μm formed on the 4340 steel surface after the PeP treatment. The nanocrystalline surface layer formation is triggered by the rapid freezing of the local melting caused by the process. It should also be noted that internal compressive stress remains in the surface layer. However, Yerokhin et al. [48] found that by applying pulsed PeP technology, it is possible to reduce both the compressive residual surface stress and surface roughness, using a 10% sodium bicarbonate solution at a temperature of 70 $^{\circ}\text{C}$ (Fig. 16). The crater appears on the treated surface due to the discharges occurring during the polishing process. The sample d ($f = 10$ kHz; $\delta = 0.2$) micrograph surface has visible blackened segments, which can be associated with thermally induced surface oxidation processes, meaning that the plasma discharge conditions were unstable. Furthermore, Zhuo et al. [78] confirmed that PeP technology could be applied to surface polish high-carbon microalloyed steel materials. It not only effectively removed the oxide scale from the metal surface but also improved the gloss level and wear resistance. Belkin [61] found that both the corrosion and wear resistance of nitriding carbon steel were improved after PeP. The original oxide layer containing micro-cracks and pores was removed after polishing.

5.3 Aluminum and its alloys

Most of the reported studies on the polishing of aluminum and its alloys are concerned with the optimization of processing

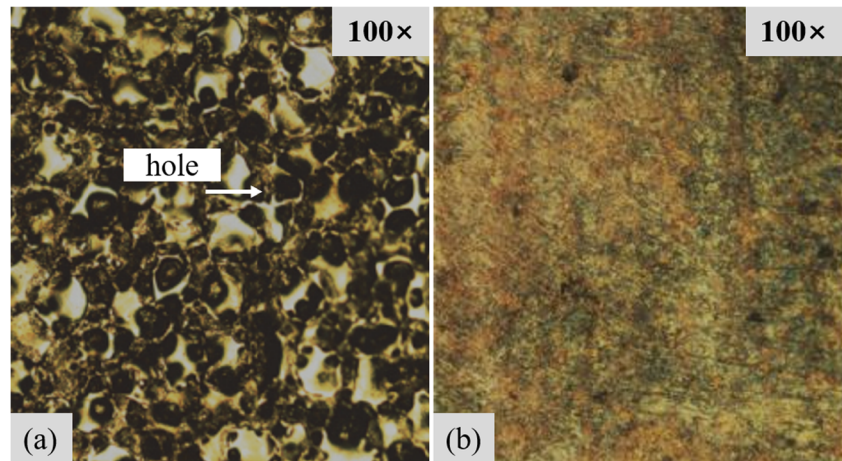
parameters. Duradji et al. [64, 79] concluded that the best effects for aluminum polishing could be achieved using the aqueous solution containing 10% NH_4Cl , 4% KCl , and 3% oxalic acid, employed at a voltage of 300 V and temperature of 60 $^{\circ}\text{C}$ to 80 $^{\circ}\text{C}$. It is evident that the aluminum anode polishing and the copper coating removal (from the cathode) coincide, but the mechanism remains unclear. Zakharov and Korotkikh [51] analyzed the literature, collected statistics on the composition of PeP electrolytes used in aluminum alloy D16 process, and found that the polishing only occurs in nitrate-based electrolytes.

At the same time, Zakharov and Korotkikh [51] developed an electrolyte composed of 4% to 5% KNO_3 , 2% to 3% $\text{C}_6\text{H}_8\text{O}_7$, and 0.5% to 1% $\text{C}_3\text{H}_8\text{O}_3$, which prevents surface etching and provides the required surface quality. Xue [80] found that the optimal aluminum alloy polishing parameters are 5-mm dive depth, 5 min processing time, and 80 $^{\circ}\text{C}$ temperature. The 3D sample surface topography before and after the polishing using optimal process parameters is shown in Fig. 17. Qi [81] polished Al alloy products using the optimal process parameters and observed improved product gloss and reduced surface roughness (from the initial 5.4 to 1.6 μm), as shown in Fig. 18.

5.4 Copper and its alloys

Plasma electrolytic polishing can reduce the surface roughness and improve surface gloss while removing the oxide layer found on the surface of copper and its alloys. In addition, it can modify the copper metal surface by improving its corrosion resistance. Bottger-Hiller et al.

Fig. 15 Microscopic observation: **a** the surface after EDM; **b** the surface after PeP (conditions: voltage of 270 V, temperature of 90°C, and processing time of 5 min) [60]



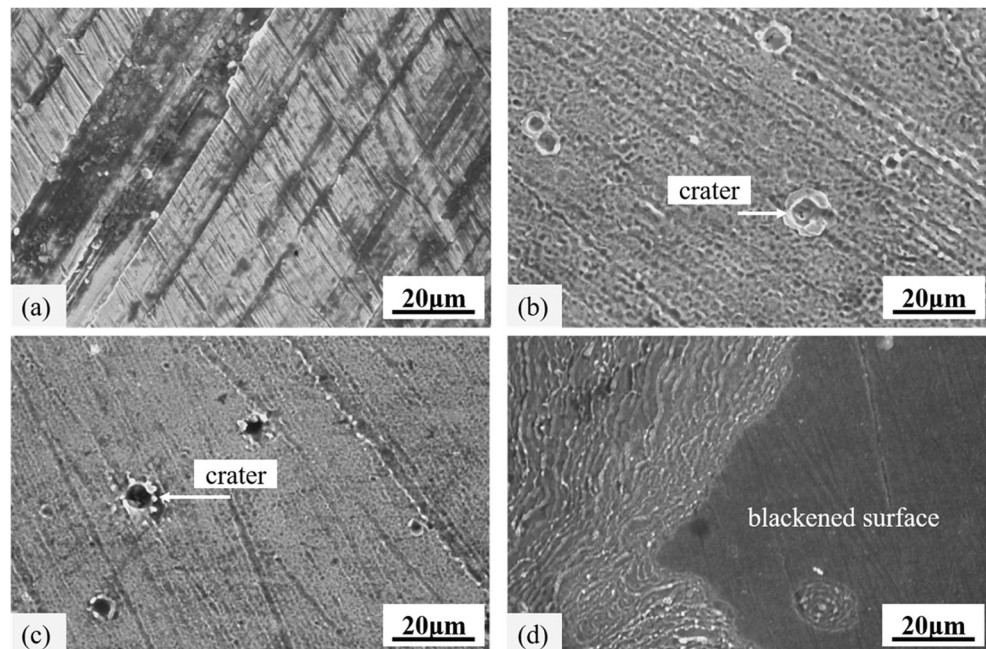
[82] transferred the PeP technique to copper polishing and applied it to copperized carbon fibers. The corroded copper sheet layer was completely removed, while the gloss was significantly increased as it was reported that the part was reflecting. Nestler et al. [39] also investigated the application of PeP on copper and its alloys. As shown in Fig. 19, PeP removes the surface materials and achieves a very smooth surface with unprecedented gloss at lower processing time. Duradji and Kaputkin [33] found that the copper material removed during the polishing process is converted into copper ions and transferred to the cathode under the influence of electric field force, forming a copper coating. Through experimental research, Huang [83] concluded that PeP could be used to reduce the brass surface roughness from 0.683 to 0.173 μm , enhancing the polished surface corrosion resistance.

Reinhardt [84] confirmed that PeP could be used to improve the corrosion resistance of copper surfaces significantly. Two key reasons for such behavior were identified—the improvement of the surface flatness and the surface layer chemical modification.

5.5 Titanium and its alloys

A fluorine salt-based electrolyte is the most often used polishing solution for the PeP of titanium and its alloys. Due to a dense and thin oxide layer formed on the surface of titanium alloys during polishing, hydrofluoric acid (HF) is used to cut the oxide layer and smooth the surface. Many researchers have confirmed that PeP can be used for titanium alloy polishing in both the medical and aviation fields. Aliakseyeu et al. [68] proposed using PeP for polishing

Fig. 16 SEM micrographs showing the surface morphologies: **a** untreated sample after grinding finishing process; **b** DC treated; **c** $f=10$ kHz; $\delta=0.8$; **d** $f=0.1$ kHz; $\delta=0.2$; where f is the frequency and δ is the duty cycle of source [48]



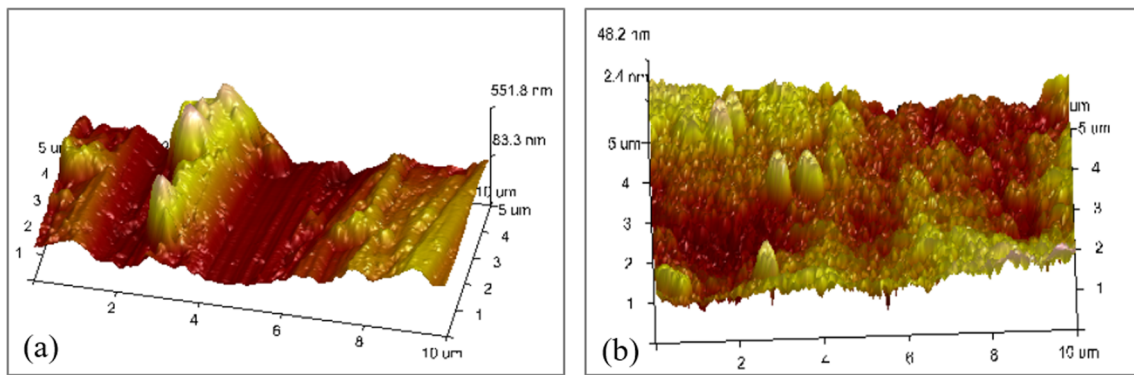


Fig. 17 3D topography of aluminum alloy: **a** before PeP; **b** after PeP (conditions: 80°C temperature, 5-mm workpiece depth, and 4 min treatment time) [80]

titanium alloy while using simple electrolyte composition based on an aqueous ammonium fluoride solution. As shown in Fig. 20a and b, the titanium sample surface scratch is removed, and the surface gloss is significantly improved after polishing. Based on the obtained results, the PeP processes of several products made of titanium alloy BT6 (Grade 5) were applied in the design of medical equipment and aircraft, as indicated in Fig. 20c.

Smyslova et al. [69] discussed the perspectives of applying PeP technology to treat the surfaces of medical implants. They found that PeP in electrolytes containing fluoride components changes the chemical composition of the Ti-6Al-4V alloy surface. After PeP, a titanium fluoride (TiF) layer forms on the surface, having positive effects on its biocompatibility. However, Smyslov et al. [85] confirmed that the oxide layer on the titanium alloy surface reacts with electrolytes containing ammonium fluoride and forms titanium tetrafluoride (TiF₄) during the PeP process. At the same time, titanium tetrafluoride is removed due to high-temperature evaporation. Therefore, the surface roughness is reduced. Zhang [86] used the PeP technology to remove the burrs found in titanium alloy blades and found that the mean surface roughness value Ra was reduced from 1.29 to 0.6 μm.

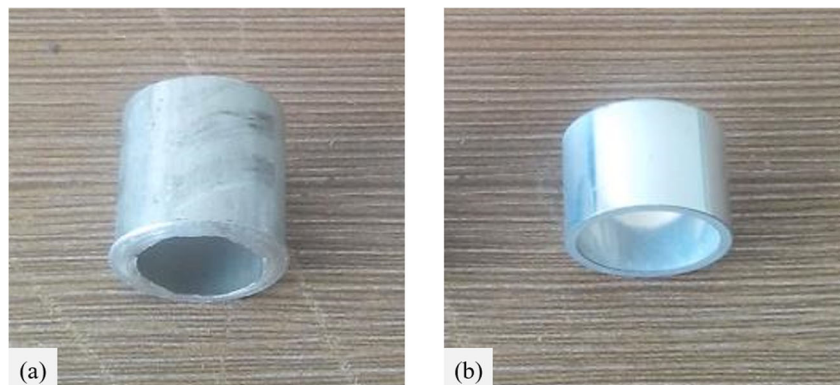
5.6 Niobium, magnesium alloys, and cobalt-chrome alloys

Plasma electrolyte polishing technology can also be used to process other metals, such as niobium, magnesium alloys, and cobalt-chrome alloys. Aliakseyeu et al. [68] found that the largest PeP polishing efficiency and surface quality for niobium can be obtained at a voltage between 280 and 300 V and current density over the range of 0.18 to 0.2 A/cm². Hoche et al. [15] indicated that the application of PeP procedures for magnesium alloy surface pretreatment leads to a significant improvement in the surface quality (as shown in Fig. 21). However, compared to mechanical polishing, the plasma polished surface exhibits a higher roughness. Researchers have provided examples [87] of the effective use of PeP to polish medical parts made of various alloys, including cobalt-chrome alloys. Using PeP technology, it is possible to achieve both defect-free and smooth surfaces within minutes.

5.7 Coating removal

Coatings are widely applied to protect various surfaces of cutting and forming tools, as they are highly resistant to temperature, wear, and corrosion. However, coating removal is

Fig. 18 Examples of Al alloy products: **a** before PeP; **b** after PeP (conditions: 80°C temperature and 1 min treatment time) [81]



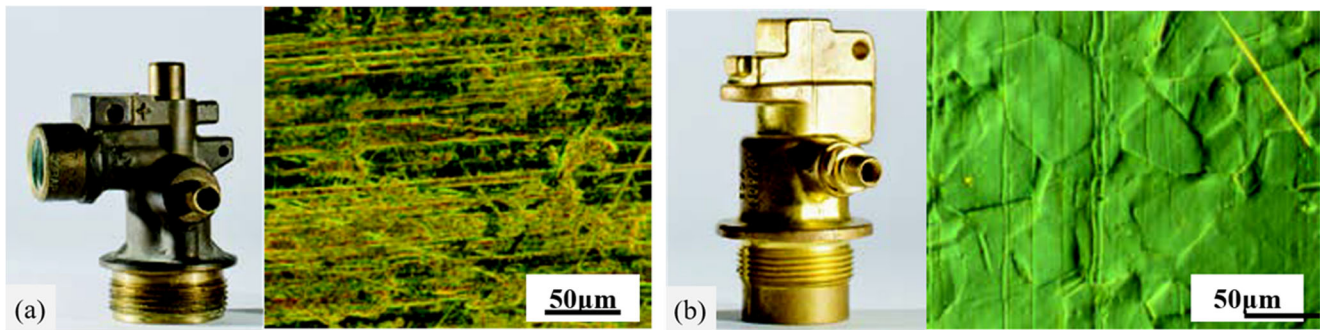


Fig. 19 Brass part and microscopic images: **a** before PeP; **b** after PeP [39]

necessary if the coating deposition process was incorrect or when the coating properties deteriorate during the operation. Based on the literature, the PeP technology can also be used in renovation technologies, primarily to remove coatings with deteriorated properties [12, 88, 89].

The remaining tool base contamination will affect the adhesion of the subsequent coating. Uhlmann et al. [90] proposed applying the PeP technology to clean coated tools, showing that PeP process removed the turning tool contamination completely (Fig. 21). It should be added that the contamination could not be cleaned by the wet-chemical cleaning technology, which caused the rake face and cutting edge

coatings to flake off (please see Fig. 22a). However, the turning tool coating remained when treated using PeP, showing that the coating layer adhesion was increased (Fig. 22b). Finally, it was found that PeP does not influence tool micro-geometry, thereby not affecting the subsequent performance.

6 Conclusions

The plasma electrolyte polishing technology improves the surface quality of metallic materials by providing enhanced mechanical and corrosion resistance properties, making it

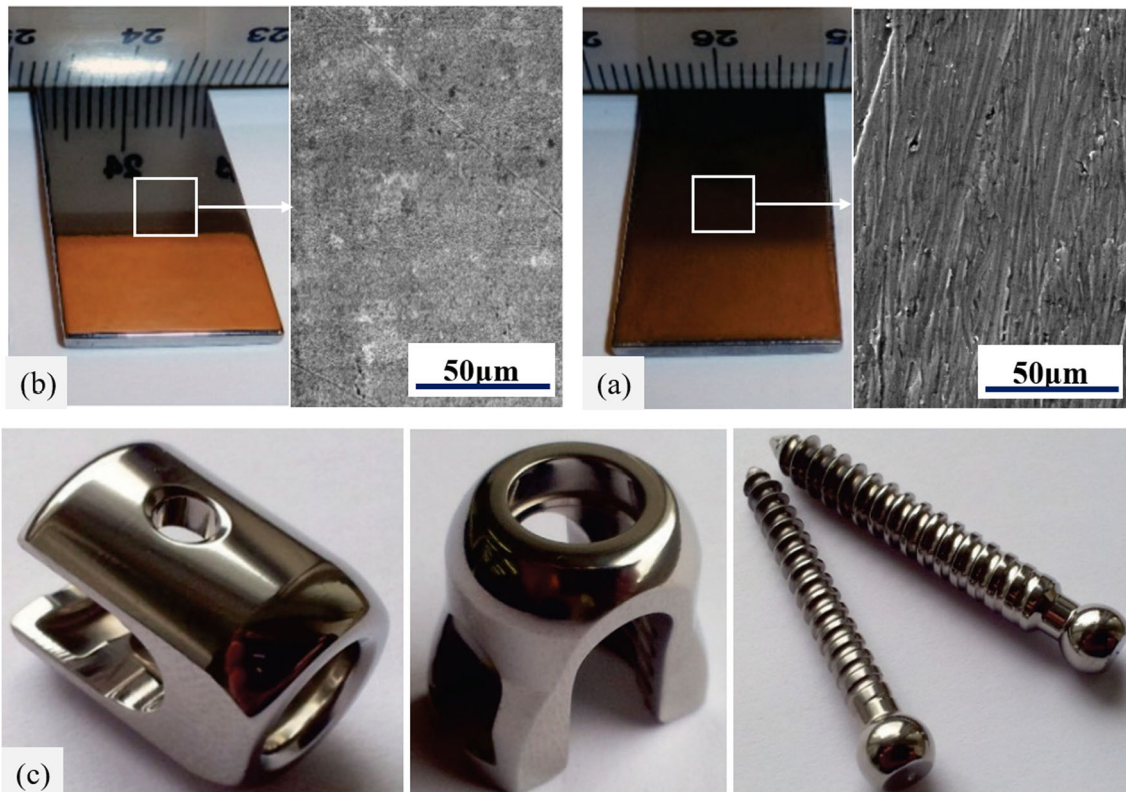


Fig. 20 Surface macro- and micro-photographs of titanium samples before and after PeP: **a** before PeP; **b** after PeP at a voltage of 300V and initial temperature of 90°C; **c** examples of PeP products made of titanium alloy BT6 [68]

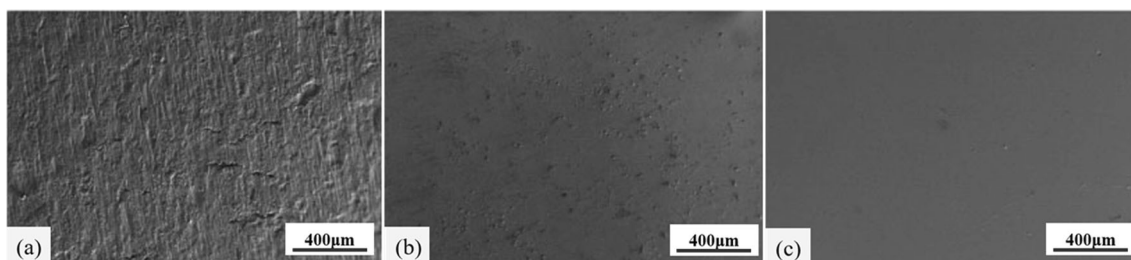


Fig. 21 SEM images of the magnesium alloy: **a** untreated; **b** after PeP; **c** after mechanical polishing [15]

useful in various industrial areas. From an industrial viewpoint, the process offers an economical and environmentally friendly method for polishing metallic surfaces. Based on the literature reviewed in this paper, the following conclusions can be drawn:

1. The underlying principle of PeP technology is that PeP mainly removes materials by forming a gas layer on the surface of the metallic part, followed by generating a plasma discharge, and surface bombarding.
2. High electrolyte voltage and temperature are key factors affecting the formation of a stable gas layer and the occurrence of the plasma discharge.
3. Many parameters influence the polishing process and the subsequent polishing results, such as electrolyte type, electrical source, process parameters, pretreatment, cathode, hanger, and workpiece, among others. The most significant factors affecting the surface roughness are treatment time, electrolyte, and voltage.
4. Plasma electrolyte polishing with electrolyte jet is a suitable method to polish workpieces with complex geometries and configurations, such as large flat workpieces, large cylindrical workpieces, long-length workpieces, and workpieces with deep holes or cavities.
5. PeP was successfully applied to steel, aluminum, copper, and titanium and their alloys, as well as several other metals and surface coatings. Furthermore, it was shown

to effectively improve both the surface quality and performance of parts.

7 Prospects

The following PeP prospects are proposed based on this review paper:

1. Studies on polishing theory are mainly experimental and lacking in theoretical formulas, making it hard to achieve the actual engineering application. Furthermore, specific composition, function, and luminescence mechanism of the gas layer during polishing remain unclear. Online monitoring of changes in phenomena and process parameters during polishing is still unexplored, but provides a plethora of possibilities for future theoretical research. Thereby, the systematic theoretical research of the polishing process should become an important research direction in PeP technology.
2. Additional modeling and simulation studies should be emphasized to enable the prediction of optimum process parameter values, as it would enable achieving the expected workpiece improvements and reduce the time and cost of experiments. This work can be carried out by using

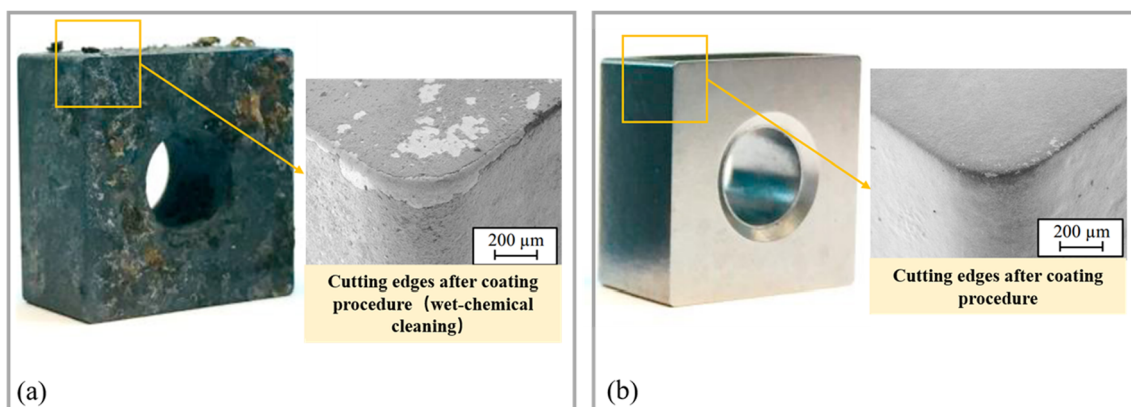


Fig. 22 The cutting tool and SEM images of cutting edge: **a** contaminated tool, **b** contaminated tool after PeP [90]

commercial finite element programs such as COMSOL or ANSYS.

3. Plasma electrolytic polishing has no harmful effects on cell life, paving the way for its application in the surface finish machining of medical parts. Introducing PeP technology into the industrial bio-manufacturing process chain is certainly among future development trends.
4. Plasma electrolytic polishing technology coupled with either the ultrasonic or magnetic fields is still an unexplored area, presenting valuable future research opportunities.

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Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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