



Article

Different Plasma Polishing Regimes Induced by Electrolytic Flow

Adel Ghezri ^{1,2,*} , Yan Scholl ² , Nick Huber ², Killang Pratama ³, Thomas Nelis ^{2,3}, Jürgen Burger ¹ 
and Cedric Bessire ²

¹ School of Biomedical and Precision Engineering, Bern University, 3010 Bern, Switzerland

² School of Engineering and Computer Science, Bern University of Applied Science, 2501 Biel, Switzerland

³ Laboratory of Mechanics of Materials and Nanostructures, Empa—Swiss Federal Laboratories for Materials Science and Technology, 3602 Thun, Switzerland

* Correspondence: gza2@bfh.ch

Abstract

This study investigates electrolyte jet processing of metals by plasma polishing, focusing on the polishing regimes and their governing flow dynamics, which result in different current density distributions and, consequently, different plasma polishing regimes. Experimental investigations performed at 350 V using a fixed-diameter electrolyte jet included localized current measurements and surface topography characterization, while finite element method (FEM) simulations were used to evaluate four plasma vapor–gas envelope (VGE) geometries. The experimental results revealed two distinct polishing regimes: a contact zone coinciding with the nozzle diameter, where the highest local current density reached 10.8 mA/mm² and produced a maximum material removal rate of 1.17 μm/s, and a surrounding electrolyte splash zone extending to approximately twice the nozzle diameter, where the local current density progressively decreased to 2.6 mA/mm², corresponding to a minimum material removal rate of 0.16 μm/s. Unlike previous studies the numerical simulations showed that a constant plasma vapor–gas envelope thickness of 15.8 μm provided the closest agreement with the experimentally measured polishing profile. Based on the combined experimental and numerical results, the contact zone is interpreted as a plasma-dominated region characterized by high current density, whereas the splash zone is interpreted as a transient plasma regime in which electrochemical polishing increasingly dominates as current density decreases. This study improves the understanding of plasma electrolyte polishing (PEP), which involves both plasma-assisted and electrochemical material-removal mechanisms. The results provide guidance for improving surface quality and process efficiency in electrolyte-jet PEP of stainless steel.

Keywords: current density; surface microstructure; splash zone; plasma electrolytic polishing jet; finite-element simulation; stainless steel; vapor gas layer



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1. Introduction

Plasma Electrolytic Polishing (PEP) has emerged as a promising surface finishing technique, offering several advantages [1] over conventional electrochemical polishing (EP) for high-performance surfaces in the nanometer roughness regime [2]. One technical advantage of this process is the elimination of the need for precleaning to remove organic contaminants. Furthermore, enhanced surface quality is achieved in comparison with that of Electrochemical polishing EP [3,4]. In comparison to EP, PEP uses electrolytes without toxic acids such as hydrofluoric acid and sulfuric acid, thereby reducing concerns related to environmental and safety handling issues [5]. The novel jet-based adaptation, the Plasma

Electrolytic Polishing Jet (PEP-Jet) process, is distinguished by its capacity for localized and selective polishing to process complex geometric shapes with high efficiency and precision [6]. It displays an increased polishing rate for surface roughness reduction [7] and offers versatility in polishing applications. These characteristics, in conjunction with the potential for targeted zonal material removal and intricate geometries including cavities, position PEP-Jet as an innovative process for advanced metal finishing [2,8]. Although PEP-Jet offers these advantages, it also presents a distinctive set of hydrodynamic challenges [5,9]. The dynamics of the jet flow exert a significant influence on the geometry and behavior of the contact zone [10], which in turn affects the distribution of the current density and thus the overall polishing efficiency of the process [10]. The geometry of the electrolyte impact zone is of pivotal importance in determining the resistance between the metal interface and the nozzle outlet of the electrolyte and thus the current distribution, feeding the plasma with energy [11].

The stability and persistence of the plasma are strongly influenced by hydrodynamic parameters, which regulate the uniformity and thickness of the plasma vapor-gas envelope (VGE) layer at the contact zone [12]. However, thermal effects were not explicitly modeled or experimentally quantified in the present study and are therefore beyond its scope. Likewise, the electrolyte composition, applied voltage, electrolyte flow conditions, and jet hydrodynamic characteristics were maintained constant throughout this work, as these process parameters had been previously optimized and validated in our earlier studies. The current density distribution is of critical importance in sustaining the plasma and thus determining the local polishing rate [10]. Areas of higher current density exhibit enhanced plasma activity and energy delivery, which facilitates more efficient material removal [10]. In this region, the roles of plasma and electrochemical polishing differ substantially [13]. Plasma polishing, characterized by intense localized energy delivery, dominates in the central contact zone, enabling rapid and precise surface modification [13]. By contrast, the splash zone exhibits a dynamic interplay between intermittent plasma-assisted polishing and more frequent electrochemical polishing, with plasma events forming less often and dissipating more rapidly, resulting in a slower polishing response [13].

Despite the growing interest in Plasma Electrolytic Polishing (PEP) and its jet-based adaptation (PEP-Jet), the fundamental mechanisms governing localized material removal remain insufficiently understood. In particular, the relationship between electrolyte hydrodynamics, current density distribution, and vapor-gas envelope (VGE) geometry has not yet been experimentally correlated with the resulting polishing profile. Previous studies have primarily focused on process optimization or surface quality, while the physical transition between plasma-dominated polishing in the jet contact zone and the competing contributions of plasma-assisted and electrochemical polishing within the splash zone remains largely unexplained.

In this work, the plasma-assisted and electrochemical material-removal mechanisms governed by current-density localization and the geometry of the vapor-gas envelope (VGE) are investigated. Despite the growing interest in PEP-Jet polishing, the respective contributions of these mechanisms within the contact and splash zones have not yet been quantitatively distinguished [14,15]. This study addresses this gap by experimentally mapping current distribution and material removal, developing a finite element model of the VGE, and correlating experimental and numerical results to identify the governing polishing mechanisms. The resulting framework provides a mechanistic basis for improving polishing uniformity and process efficiency.

2. Materials and Methods:

2.1. Simulation

The 2D COMSOL simulation models were developed using COMSOL Multiphysics® version 6.3 (COMSOL AB, Stockholm, Sweden) to replicate the electrical configuration and material removal behavior of the PEP-Jet process. The first simulation focused on the electrical configuration and boundary conditions, illustrating the typical two-dimensional distribution of current density that characterizes the jet, splash, and plasma regions. A representative one-dimensional current density profile was extracted one micrometer above the plasma–anode interface, spanning both the plasma and splash zones.

The second simulation investigated the distribution of the material removal rate as a function of position relative to the jet's axial symmetry. The simulated removal rate profiles were fitted to the experimental data, enabling a direct comparison between the model predictions and the measured results. The plasma thickness of 150 μm adopted in Simulation A corresponds to values previously reported in the literature [5,14]. However, our experimental data indicate a much thinner VGE thickness of 15.8 μm for the PEP-Jet application, using the same electrical simulation parameters for the VGE as re-ported in [15].

2.2. Experiments

Plasma electrolytic polishing with a jet (PEP-Jet) as exposed in Figure 1 works on the same principle as in the bath based PEP, but the anodically polarized workpiece is impinged by an aqueous electrolyte jet [16]. Thereby, electrolytes required for PEP are water-based and metal-specific [17], with a typical conductivity of 80 to 140 mS/cm [18]. By applying a DC voltage, a vapor–gas envelope (VGE) is formed where the electrolyte jet hits the workpiece due to Joule heating caused by the higher current density on the work-piece. The appearance of the VGE increases the electrical resistance significantly [19] and thus, a plasma skin is built up inside the VGE on the workpiece. This plasma layer causes the removal of peaks on the surface, thus polishing the workpiece [3]. Within the PEP-Jet process, both physical plasma and electrochemical processes take place [18].

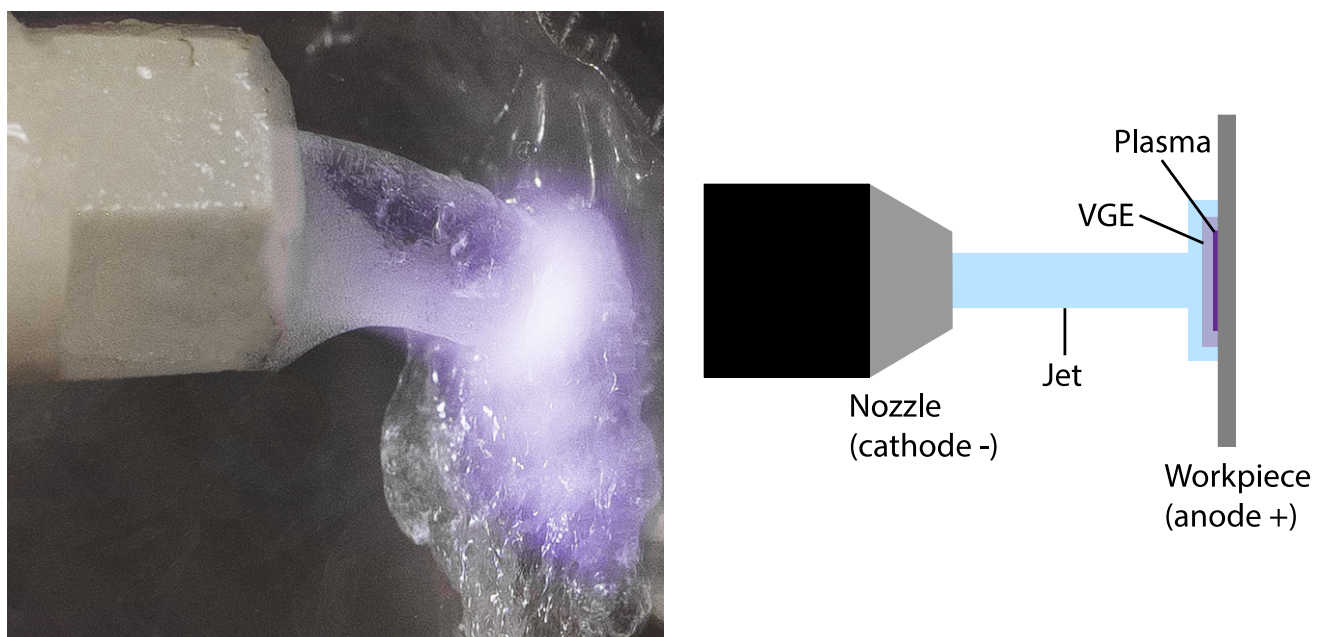


Figure 1. Experimental image and corresponding schematic representation of the PEP-Jet process, highlighting the plasma-dominated contact zone and the surrounding splash zone.

The use of an electrolyte jet instead of a bath allows overcoming these issues and enables selective plasma electrolytic polishing of metal surfaces. In the PEP-Jet configuration, specific regions of a workpiece can be polished as needed, allowing for different polishing finishes on the same workpiece. Furthermore, the electrolyte flow enables higher polishing rates than the conventional PEP bath [6].

To measure the current distribution, sixteen measurement points are integrated into the surface of the sample. The dimensions of the sample surface are $30 \times 30 \text{ mm}^2$. The measuring points consist of rods with a diameter of $\varnothing 1 \text{ mm}$ that are guided through the sample. They are aligned to reproduce the jet shape in a grid with a 1.5 mm spacing. The rods are electrically insulated from the base sample with polytetrafluoroethylene (PTFE) hoses and molded in epoxy resin to keep them in place. Both the plate and the rods for current measurement are made from austenitic stainless steel 316L (1.4404 or X5CrNiMo17-12-2) with a composition of 17% chromium, 12% nickel, and 2% molybdenum. The rods and the base plate are polished to ensure a flat surface.

The polishing process was performed at a constant voltage of 350 V. Both the base sample and all the rods are connected to the anode. The electrolyte utilized in this process is deionized water with the addition of 10% ammonium sulfate and 1.05% SA (30 wt.% stock solution). The jet had a diameter of $d_{\text{jet}} = 4 \text{ mm}$ and a length of 5 mm set by the distance of the nozzle to the surface. The jet is aimed at the central measurement point in the third row as exposed in Figure 2.

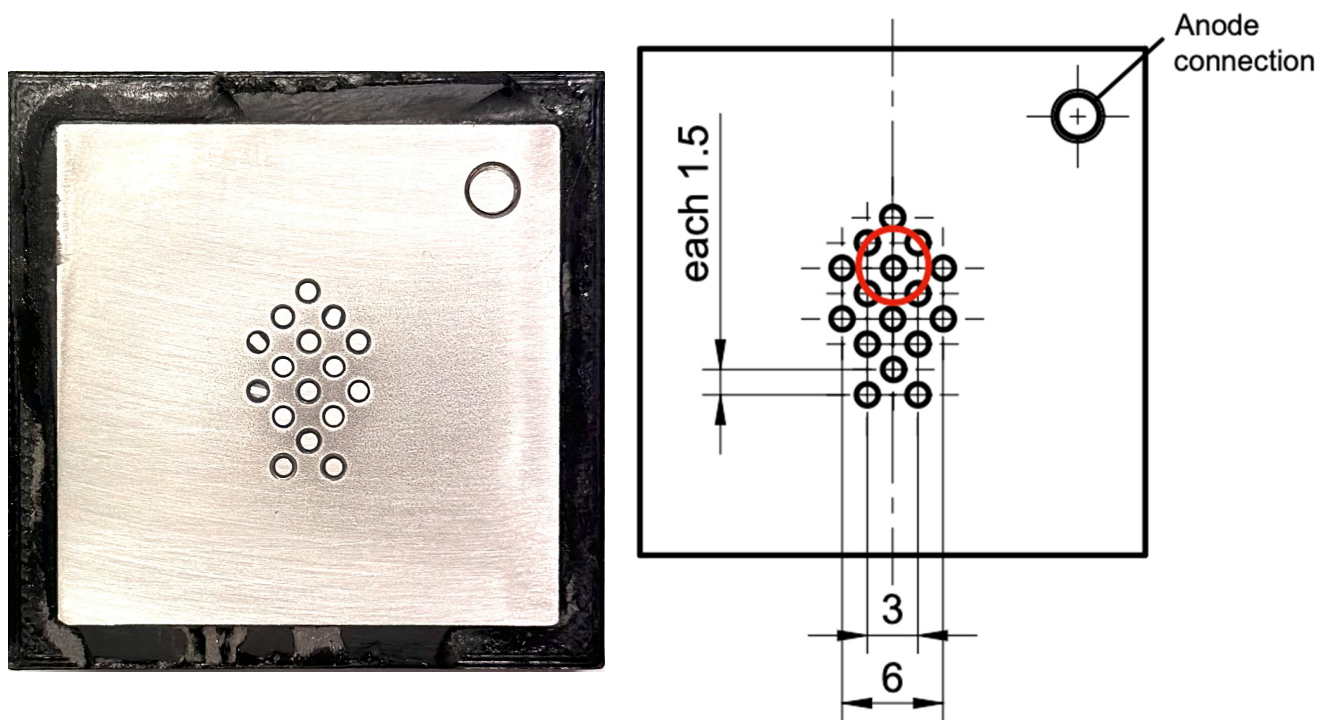


Figure 2. Image of the sample and schematic representation with distances in mm of the segmented sensor sample designed for spatially resolved measurement of the local current distribution across the PEP-Jet contact and splash zones during polishing.

The current measurements were performed using eight LEM current sensors (CTSR 0.3-P LEM International SA, Meyrin, Switzerland) based on the closed-loop fluxgate principle. Measurements were recorded every 0.1 s in two 30 s intervals, first with the upper eight sensors and then with the lower eight sensors, resulting in a total process time of 1 min.

3. Results

3.1. Current Density Distribution

A simplified two-dimensional axisymmetric model, as illustrated in Figure 3, was developed to facilitate the numerical analysis of the plasma electrolytic polishing jet process. This model represents the essential physical regions of the system, including the jet, electrolyte, plasma, and splash zones, while maintaining computational efficiency. The cathode (jet nozzle) and anode (workpiece) boundaries were defined with fixed potentials to reproduce the electric field configuration and current density distribution, while all other surfaces were treated as electrically insulated. Although the model neglects minor three-dimensional flow effects, it remains sufficiently accurate to capture the main current density distribution and electrochemical behavior at the plasma-anode interface. Furthermore, the increase in electrical resistance within the splash zone is effectively reproduced by the simplified model. This increase is due to the presence of a thin, conductive electrolyte film in this region. The plasma discharge terminates at the boundary between the plasma and splash zones.

A physics-controlled mesh was employed with the finest mesh elements (minimum element size of 0.001 μm) confined to the plasma vapor–gas envelope (VGE) and the plasma–electrolyte interface to accurately resolve the steep current density gradients. The mesh was progressively coarsened away from the VGE using a maximum element growth rate of 1.3, a curvature factor of 0.2, and a narrow-region resolution of 10. An electric potential of 350 V was applied to the cathodic nozzle, with the workpiece defined as the grounded anode, which had a potential of 0 V. The remaining external boundaries were electrically insulated. The electric field was solved using the Electric Currents interface in COMSOL Multiphysics® version 6.3, based on the steady-state charge conservation equation in conjunction with Ohm’s law, thereby calculating of the spatial current density distribution.

The computational domain consisted of a central contact zone surrounded by a splash region extending to approximately twice the contact-zone width. Figure 3b shows the calculated one-dimensional current density profile extracted 1 μm above the plasma workpiece interface, while Figure 3c presents a magnified view of the plasma region, illustrating the highly localized current density beneath the jet center and its progressive decrease toward the splash region.

Thus, the model was designed to approximate this behavior under steady-state, static conditions, providing a practical and physically meaningful representation of the PEP-Jet system. Consequently, the model reliably illustrates how jet geometry and electrical configuration influence the localized current and removal rate characteristics of the PEP-Jet process. The subsequent section provides a comprehensive description of the components depicted in Figure 3. Specifically, Figure 3a presents the electrical configuration and boundary conditions of the PEP-Jet system. The anode is at 350 V, while the cathode is grounded. The jet electrolyte, splash electrolyte and plasma layer are located close to the anode. This configuration effectively mimics the electrolyte distribution within the PEP-Jet process: the jet defines the localized contact zone, and the surrounding splash contributes to the current path. The electrical insulation on both sides maintains the current path, ensuring that it remains confined to the plasma and electrolyte regions.

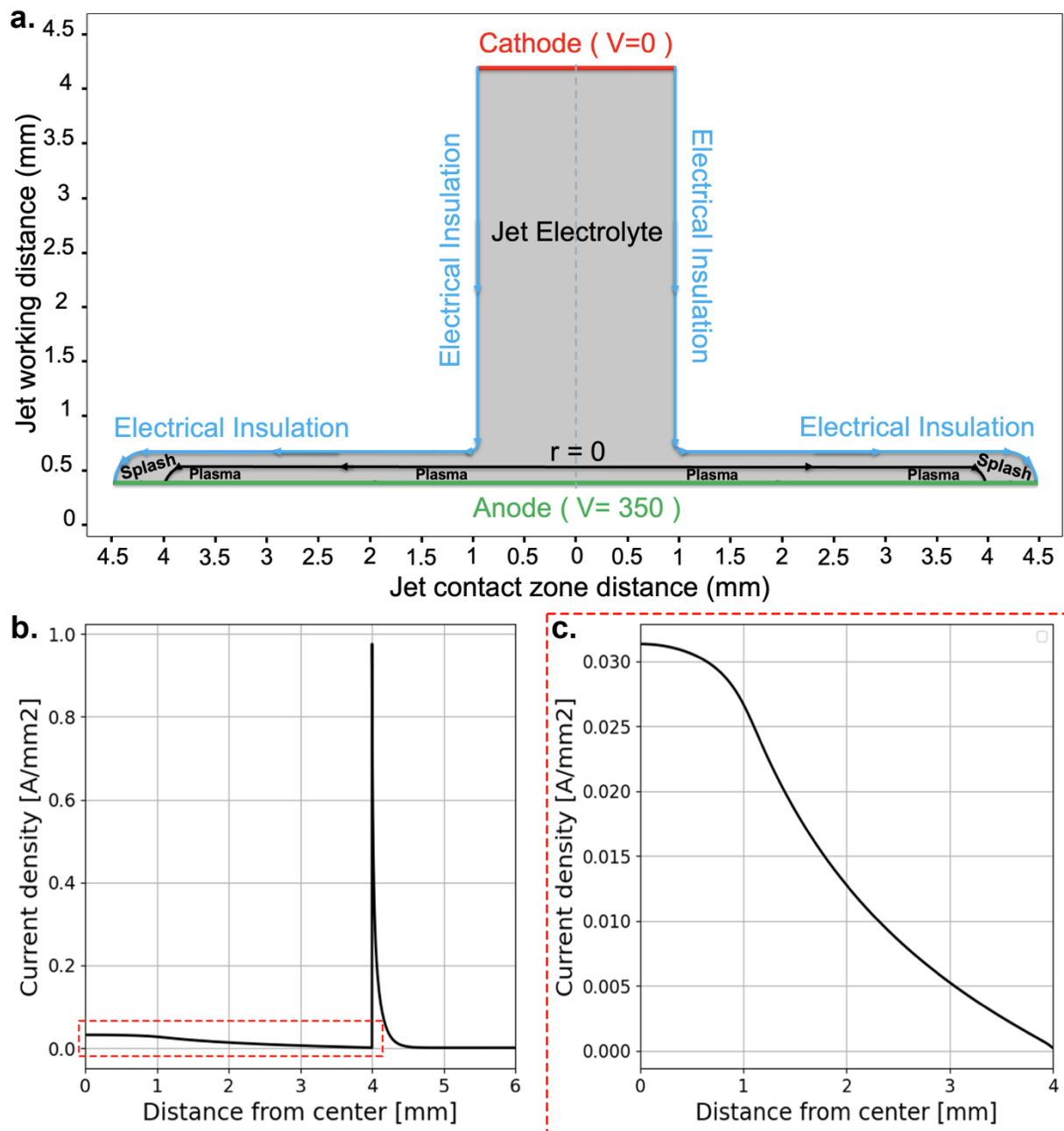


Figure 3. (a) Electrical configuration and current density distribution of the PEP-Jet model. (b) One-dimensional current density profile across the plasma and splash zones. (c) Magnified view of the current density profile in the plasma zone.

Plasma formation in PEP-Jet alters the current density, thereby localizing the reaction at the plasma-anode interface. While the presence of plasma introduces physical effects that change material removal, the mass of the material removed per unit charge still adheres to Faraday's law. In order to estimate the rate of etching or removal of polished materials, a one-dimensional current density profile shown in Figure 3b was employed. In this approximation, the removal rate is determined through Faraday's law for electrochemical deposition/dissolution, assuming no mechanical removal but only electrochemical processes. Figure 3b illustrates the simulated behavior of current density profiles near the plasma-anode interface during the PEP process. This simulation demonstrates a critical phenomenon: the eventual breakdown of plasma, leading to a surge in current associated with electrochemical polishing (EP). This phenomenon manifests more frequently in

the splash zone than in the contact zone as previously stated. The illustration depicts a pronounced peak in current density situated at the center of the plasma zone, where the resistance through the plasma shell is at its lowest. This region is indicative of the plasma-dominated contact zone, wherein the plasma remains quasi-stable. It has been observed that, in the majority of cases, plasma experiences intermittent breakdown. However, it has also been demonstrated that plasma rapidly recovers due to the presence of a high current density, which significantly contributes to the removal of material through plasma polishing mechanisms. However, as the distance from the center increases, the current density experiences a rapid decline due to the increased resistance of the electrolyte path, which effectively inhibits the stability of the plasma shell. This zone defines the “splash zone,” wherein the plasma becomes intermittent or breaks down with greater frequency due to the lower current density and higher resistance. In this region, the prevailing polishing mechanism undergoes a transition from a plasma-dominated to an electrochemical polishing-dominated mechanism. In contrast to the central plasma-dominated region, where plasma delivers high-energy localized polishing, the splash zone exhibits a more gradual material removal due to the occurrence of mainly an electrochemical process. The higher resistance of the water path in the splash zone has a fundamental impact on plasma stability, thereby forcing the polishing effect to shift towards electrochemical mechanisms. This transition illustrates the interplay between plasma polishing and electrochemical polishing within the PEP-jet process, wherein variations in current density directly regulate the polishing regime.

3.2. Experimental Current Density Measurements

To understand the material removal mechanisms in Plasma Electrolytic Polishing (PEP), it is necessary to correlate the process conditions with the resulting surface morphology.

For the PEP-Jet process on 316L stainless steel, the local current density is a critical parameter, as it governs the intensity of plasma discharge and the rate of electrochemical dissolution. This relationship was investigated by integrating experimental surface topography measurements with simulations of the current density distribution. Figure 4 provides an in-depth analysis of the surface structure and process dynamics of 316L stainless steel samples polished using the PEP-Jet method. Figure 4a illustrates the three-dimensional surface structure of the material post-polishing, displaying a color gradient that indicates physical depth variations. The maximum material removal rate was $1.17 \mu\text{m/s}$ at the center of the polishing footprint. The darker regions indicate areas where more material was removed, suggesting the presence of localized high-intensity regions during the polishing process. Conversely, the lighter regions indicate areas where less material removal occurred. Figure 4b shows the three-dimensional distribution of current density during the PEP-Jet polishing process. This distribution is represented by a color-coded spectrum. High-intensity zones, which are characterized by elevated current densities, indicate regions where plasma activity and electrochemical interactions are concentrated. These regions exert a direct influence on the material removal rate and surface uniformity, thereby making the current density distribution a critical factor in optimizing the process. Figure 4c depicts the two-dimensional surface structure after polishing, with a color gradient denoting the physical depth variations, mapping the polished surface. The mapping illustrates the distribution of depth variations across the sample in its current state.

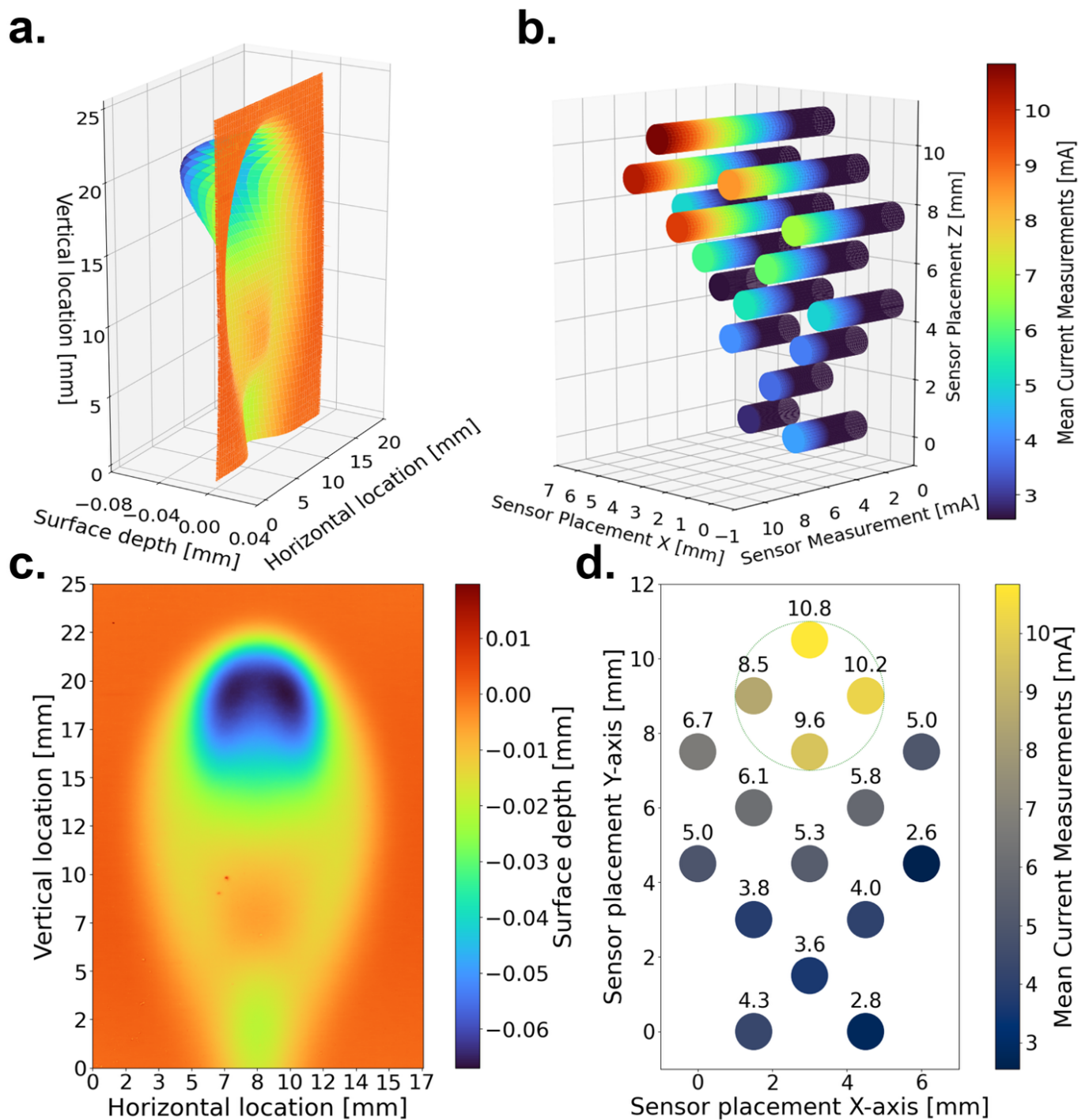


Figure 4. (a,c) Three-dimensional surface topography and corresponding two-dimensional surface profiles of stationary PEP-Jet-polished AISI 316L. The color scale indicates the local material removal depth. (b) Three-dimensional representation of the sensor array showing the mean current measurements averaged over the entire polishing duration and mapped to the corresponding sensor positions. (d) Scatter plot of the averaged sensor measurements mapped to their respective sensor locations.

The depth along the Z-axis is represented by a color gradient, wherein darker hues indicate a greater degree of material removal. The averaged current sensor measurements, recorded at regular intervals during polishing, are presented as a scatter plot in Figure 4d. The data point size and color intensity correspond to the current magnitude. The measured local current density varied from 2.8 mA/mm² at the outer splash region to a maximum of 10.8 mA/mm² in the jet contact zone, corresponding to an approximately 3.9-fold increase

in local current. Larger, darker points indicate higher current, corresponding to the contact zone of sustained plasma activity. Smaller points indicate lower current in the splash zone, where plasma stability is reduced.

This pronounced spatial current gradient closely follows the measured material removal profile, demonstrating that regions exhibiting the highest local current also experience the highest material removal. Collectively, the data presented in Figure 4 establish a correlation between localized current distribution, plasma activity, and the resulting surface morphology, which is critical for optimizing the PEP-Jet process for improved uniformity and efficiency.

The relationship between localized current density and material removal rate is fundamental to the Plasma Electrolytic Polishing (PEP) mechanism. To quantitatively investigate this relationship in the PEP-Jet process, the spatial distribution of current density was correlated with precise measurements of the resulting surface topography. This analysis tests the hypothesis that the intensity of the plasma-electrolyte interaction, as indicated by current density, directly governs the dissolution rate and final surface profile. This correlation is presented in Figure 5 providing a detailed visual representation of the current density distribution and the corresponding surface depth profiles observed during the PEP-Jet polishing process. This analysis elucidates the interplay between material removal rates and localized current density, which is a defining characteristic of the PEP-Jet mechanism. Figure 5a illustrates the depth profile along the Y-axis, demonstrating the variation in material removal across distinct positions on the workpiece. The red axis indicates the current density measurements as a percentage of the total current flow, which were monitored at three sensor locations along the Y-axis. Peaks in the current density distribution are indicative of deeper removal regions, thereby emphasizing the direct relationship between higher current densities and more significant material dissolution. This observation is consistent with the hypothesis that the localized plasma-electrolyte interaction in the PEP-Jet process governs the spatial distribution of energy between the contact and splash zones, thereby enabling efficient and controlled material removal. Figure 5b provides an additional perspective on the material removal process, as demonstrated by the depth profile along the X-axis. Similarly, the red axis represents the current density percentage, as recorded by four sensors positioned along the X-axis. The profile demonstrates a relatively uniform depth distribution, indicating effective control over the jet parameters, including nozzle geometry, flow rate, and working distance. The observed asymmetries in the current density are attributed to expected process variabilities, including gravitational effects on the electrolyte and minor system turbulence. Concentrated plasma activity at the jet impact site results in efficient material removal, which correlates directly with regions of higher current density. Understanding the correlation between current density distribution and removal depth is critical for process control. Specifically, this knowledge enables the design of optimized jet-sweeping patterns that maintain a uniform, time-averaged current density across the surface. This is essential for achieving homogeneous material removal. The uniformity of the observed profile confirms that the selected process parameters, such as working distance, flow rate, and voltage, are effective for stable operation. This consistency underscores the reproducibility of the PEP-Jet technique under these conditions.

Understanding the transient electrical behavior during the PEP-Jet transition is critical for process optimization because the stability of the plasma sheath directly affects polishing efficiency and uniformity. A comparative analysis of the power supply current and localized sensor measurements was performed to distinguish the contributions of the high-intensity jet contact zone from those of the surrounding splash zone and to deconvolute the total system current. This analysis is presented in Figure 6 which compares the current flow dynamics observed in two distinct experiments, with a particular emphasis on the data

obtained from the top and bottom sensors and the power supply. The graph depicts three datasets: the sum of the currents measured by the top and bottom sensors and the total current supplied by power supply. The progression of the PEP-Jet process is captured through distinct phases, as illustrated by the measured current profiles. In the initial phase, a pronounced spike in current (green line) occurs due to the ramp-up of voltage and high resistance, marking the start of the electropolishing (EP) process at low voltage. During this period, the current supplied by the power source increases to its maximum, as seen in the green line, while sensor-specific measurements (blue and orange lines) show corresponding initial spikes. The blue line, which denotes the top sensors in the jet contact zone, consistently exhibits higher values compared to the orange line, which reflects the splash zone currents.

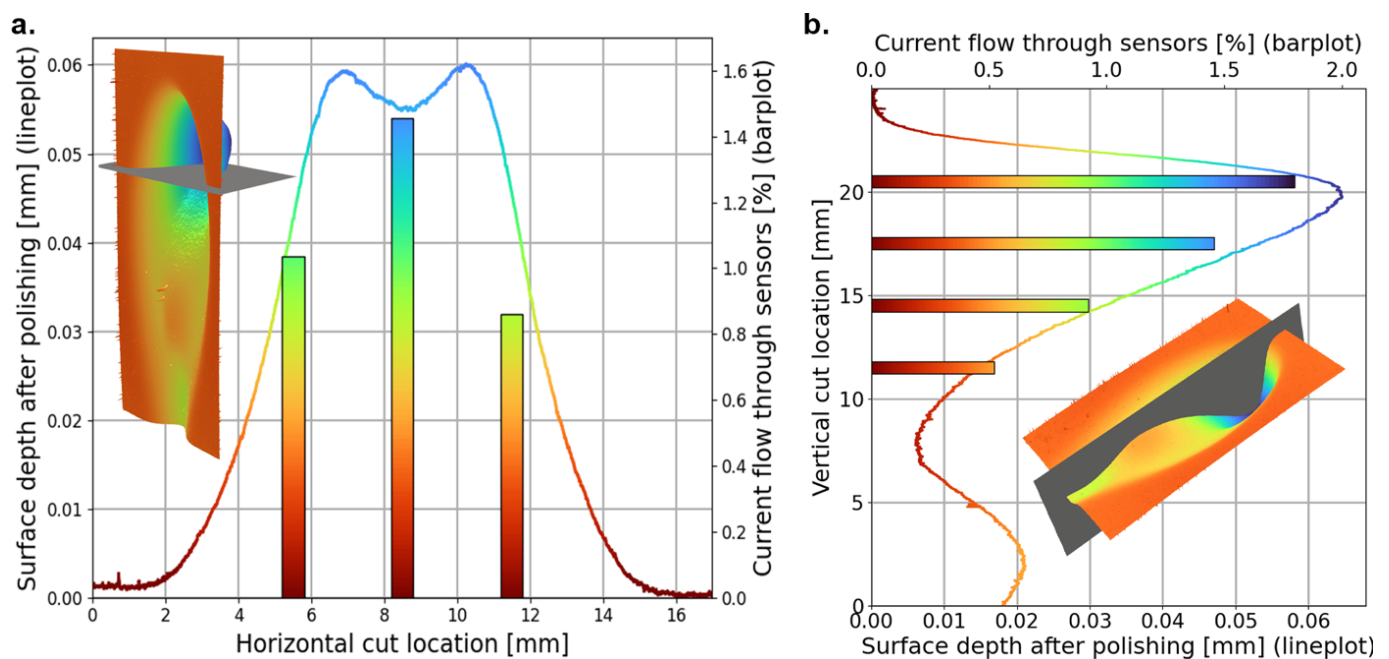


Figure 5. (a) Display the surface depth profile along the Y-axis, representing a cross-section cut along the Y-axis that is monitored by three sensors. The red axis indicates the current density measurements and the percentage of current flow through the sensors. (b) Display the surface depth profile of the polished surface along the X-axis, representing a cross-section cut along the X-axis and measured by four sensors. Similarly, the red axis illustrates the current density measurements and the percentage of current flow through the sensors.

This discrepancy underscores the more intense polishing activity in the contact zone where the jet directly interacts with the workpiece. As the process transitions into the stable phase, plasma ignition occurs, thereby initiating the plasma electrolytic polishing (PEP) regime. During this phase, the plasma sheath forms and sustains the system, leading to relatively steady current values across all measurements. The green line reflects this stability in the power supply output, while the blue and orange lines stabilize as well, maintaining their difference due to the contrasting conditions between the contact and splash zones.

Finally, in the end phase, the voltage ramp-down introduces pronounced peaks in current due to the rapid decrease in voltage and low electrical resistance in the system. Additionally, smaller transient peaks emerge during this stage, likely attributable to plasma dissipation and the system's reversion to baseline electrochemical activity. The interplay between plasma, voltage, and current throughout the PEP-Jet process is vividly captured by these dynamic changes in the green, blue, and orange lines. These current fluctuations

are a direct consequence of variations in the stability of the plasma sheath, which is highly sensitive to the applied voltage and the interaction between the local electrolyte and the jet. This instability manifests as transient changes in the effective contact area between the plasma and the workpiece, resulting in oscillations in the current density. The observed current density distribution patterns align with the theoretical PEP-Jet model, which predicts a high-current-density contact zone with stable plasma discharge and efficient material dissolution. In contrast, the low-current-density splash zone, which has intermittent plasma activity and diminished removal efficiency.

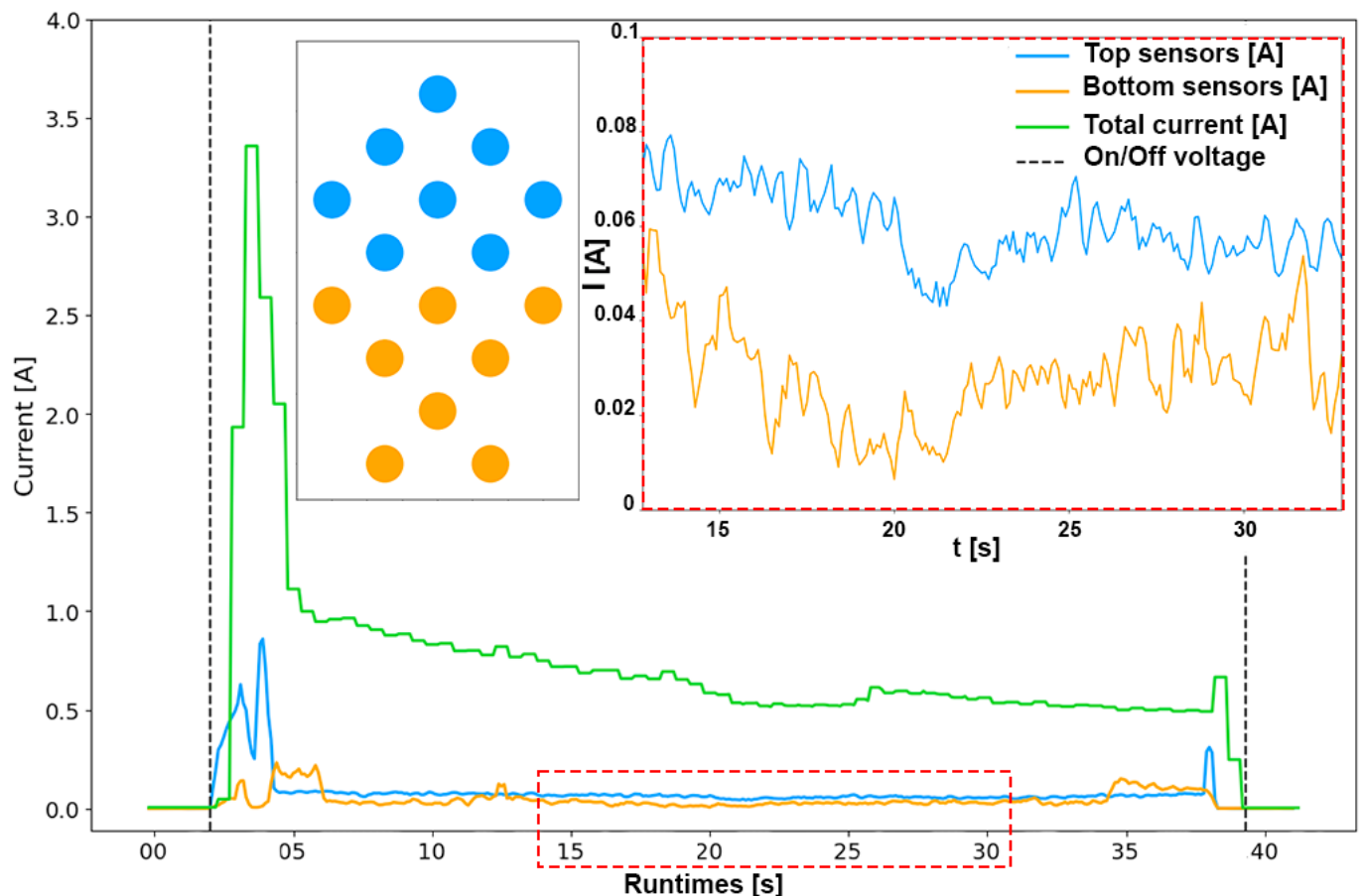


Figure 6. Comparison of the average total current supplied by the power source and the summed currents measured by the upper and lower sensor arrays. The enlarged interfacial view highlights the current difference between the contact and splash zones.

3.3. Surface Characterization

The PEP-Jet process is highly effective due to a significant radial gradient in energy density. This gradient creates two distinct polishing zones: the high-intensity contact zone and the low-intensity splash zone. This dichotomy is clearly visible in the SEM analysis shown in Figure 7.

The central photograph shows a macroscopic image of the PEP-Jet in contact with the workpiece. Figure 7a the micrograph shows the contact zone of the PEP-Jet process, with a roughness value of 81 nm, corresponding to the central region where the jet directly impinges on the stainless-steel surface. The microstructure appears distinctly modified, with uniformly exposed grains and etched grain boundaries on the surface, indicating intense localized material dissolution. The homogeneity of the etched features suggests that plasma polishing with high current density dominate the polishing action in this zone. In contrast, in Figure 7b the micrograph depicts the splash zone, which is located outside the

primary jet–surface interaction region with a roughness value of 150 nm. This zone lacks pronounced grain boundary definition, with lower current density, the plasma breaks down more often and thus this zone is predominantly governed by electrochemical polishing [2]. The pronounced microstructural features indicate preferential intragranular attack, suggesting that the plasma-assisted mechanism locally interacts with and removes material within the grain interiors [2,7]. This behavior differs from conventional electrochemical polishing, where material removal is primarily governed by anodic dissolution and preferential leveling of surface asperities, generally resulting in a smoother and more homogeneous surface without comparable exposure of intragranular features [20]. Accordingly, the relatively featureless morphology observed in the splash zone (Figure 7b) supports the predominance of electrochemical polishing in this region. These morphological differences provide further evidence for the spatial transition from plasma-assisted material removal in the contact zone to predominantly electrochemical dissolution in the surrounding splash zone.

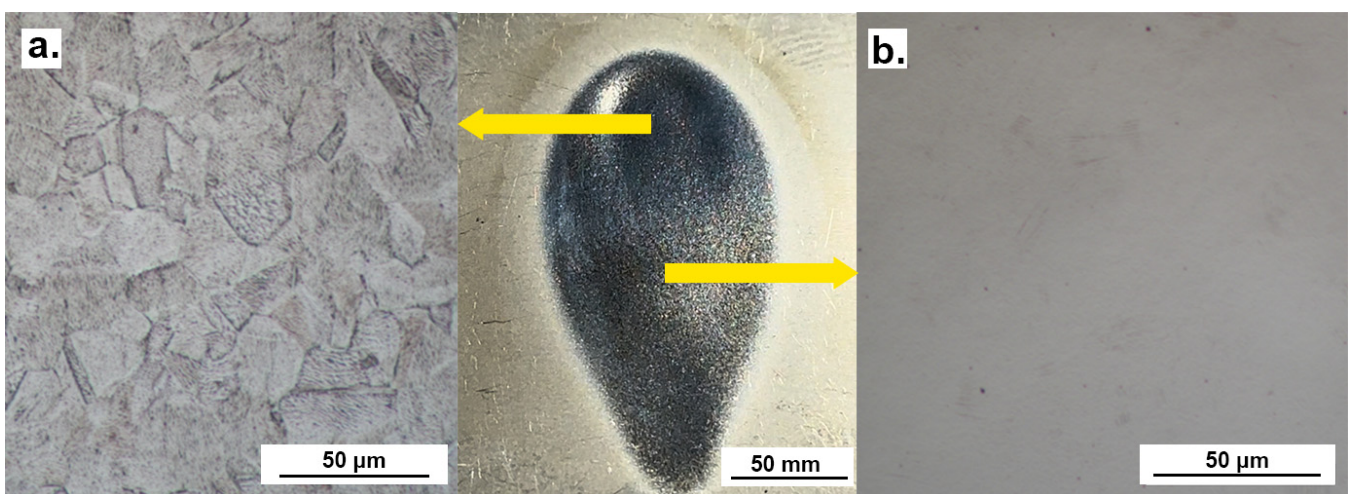


Figure 7. SEM micrographs of the PEP-Jet polishing footprint showing the surface morphology of (a) the central contact zone and (b) the surrounding splash zone. The central photograph shows the overall polishing footprint, and the yellow arrows indicate the corresponding observation areas.

3.4. Determination of Plasma and Splash Geometry

To characterize the plasma and splash geometries generated by a controlled electrolyte jet of $d_{\text{jet}} = 4$ mm, jet length of 5 mm, and a velocity of $1.7 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}$, a number of configurations were evaluated as part of the simulations conducted. A uniform set of parameters was implemented across all models, with the splash length fixed at 6 mm, the plasma length set to 4 mm, and the plasma thickness defined as $150 \mu\text{m}$ [5].

The fitting procedure was performed without introducing empirical correction factors; only the VGE thickness distribution was modified while all remaining simulation parameters were kept constant. Assuming that the local material removal rate is proportional to the current density according to Faraday's law:

$$m = \frac{M}{nF\rho} J$$

where m is the local removal rate, M is the molar mass, n is the number of transferred electrons, F is Faraday's constant, ρ is the material density, and J is the local current density, the predicted removal profiles were calculated along the radial direction extending from the jet center ($x = 0$) to the splash boundary ($x = 4$ mm). The calculated profiles were directly compared with the experimentally measured polishing profile obtained from the stationary

PEP-Jet experiments. The agreement between experiment and simulation was assessed by comparing both the peak removal rate and the spatial evolution of the removal profile.

In Simulation A, the plasma thickness was maintained at a constant value of 150 μm throughout its length. In Simulation A* the thickness was reduced to a constant value of 15.8 μm . In Simulation B a gradient in thickness was introduced, with a minimum of 15.8 μm and a maximum of 150 μm over the 4 mm length of the plasma. Simulation C combined constant and gradient profiles. The initial 1 mm of plasma length maintained a constant thickness of 15.8 μm , while the remaining 3 mm exhibited a gradual increase in thickness, ranging from 15.8 μm to 150 μm . This approach enabled the investigation of both uniform and variable plasma profiles and their effects on polishing. The simulation results are presented in Figure 8.

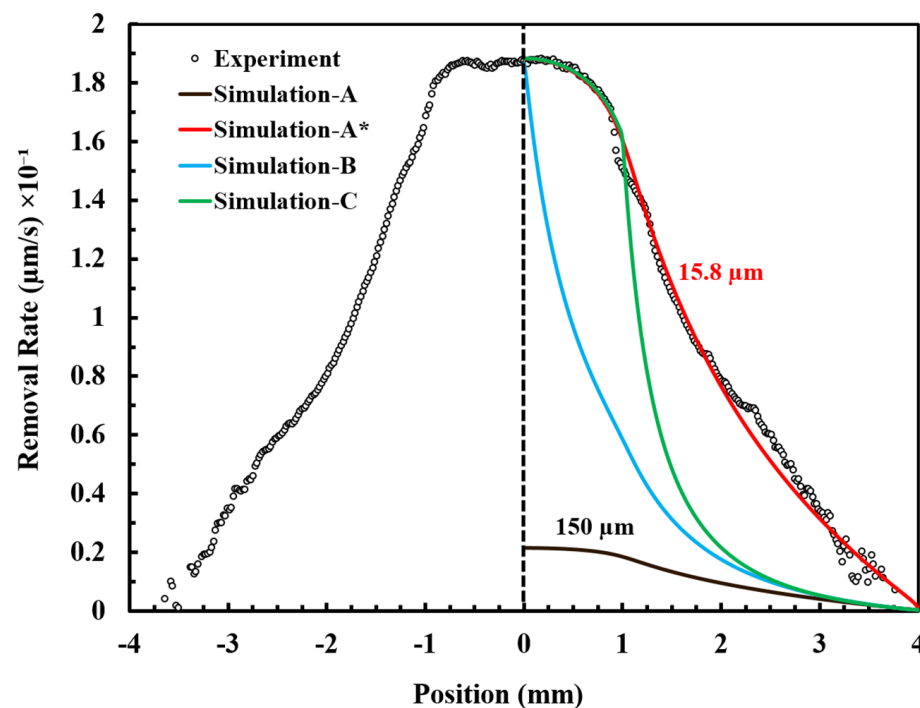


Figure 8. Calculated removal rate profiles from various simulation model (solid line) as a function of position from the axial symmetry ($x = 0$). The simulation results are fitted to experimental data. The plasma thickness for Simulation-A and Simulation-A* are 150 μm and 15.8 μm , respectively.

As illustrated in Figure 8 and Table 1, the plasma-splash geometry for Simulation A (plasma thickness of 150 μm) and Simulation B exhibits the least degree of alignment with the experimental data. In Simulation C, the degree of fitting is optimal within the constant plasma regime, extending up to 1 mm from the axis of symmetry. However, it significantly declines within the gradient plasma regime. The simulated results most closely match the experimental data when a constant plasma-vapor-gas envelope thickness of 15.8 μm is assumed (Simulation A*). Based on these findings, the plasma-splash geometry model with a constant envelope thickness (Simulation A) was selected as the most appropriate configuration for the remainder of the study. Subsequent modifications were applied to the plasma and splash geometries, specifically to thickness and length, to determine the optimal fitting conditions.

Table 1. Summary of the VGE geometries investigated in the finite-element simulations. The table presents the assumed thickness distributions and their agreement with the experimentally measured polishing profiles.

Simulation	Contact Zone (0– ± 2 mm)	Splash Zone (± 2 – ± 4 mm)	Plasma Thickness	Agreement with Experiment
A	Constant	Constant	Constant 150 μm throughout the contact and splash regions	Poor
A*	Constant	Constant	Constant 15.8 μm throughout the contact and splash regions	Excellent fit
B	Linear increase from the jet center	Linear increase toward the splash boundary	15.8 μm at the jet center (0 mm), increasing continuously to 150 μm at ± 4 mm	Poor
C	Constant 15.8 μm within the contact zone	Linear increase throughout the splash zone	Constant 15.8 μm from 0 to ± 2 mm (jet diameter = 4 mm), followed by a linear increase to 150 μm at ± 4 mm	Moderate

4. Discussion

The findings of this study provide new insights into PEP-Jet polishing mechanisms, especially the relationship between current density within the electrolyte jet and material removal. This work examines the transient behavior of plasma and its effect on edge formation in PEP-Jet, which is governed by the interaction between electrochemical and physical polishing [21,22]. The results identify two distinct polishing zones, corresponding to the plasma behavior in the jet core and the electrolyte splash zone, as previously indicated [2,6]. As shown in Figure 4 and supported by simulation, the center of the jet is plasma-dominated because the high local current density promotes and sustains the formation of the vapor–gas envelope (VGE), enabling plasma-assisted material removal. In contrast, the outer regions are predominantly governed by electrochemical polishing, as the lower current density is insufficient to sustain plasma formation, leaving direct electrolyte–workpiece contact and favoring anodic dissolution.

In the central contact region, the combination of high local current density and the reduced resistance due to the shorter distance between the anode and cathode as shown in Figure 3a favors frequent plasma initiation and breakdown, thereby enhancing plasma-driven physical etching while confining electrochemical dissolution to shorter time intervals. However, as processing proceeds, the continuous growth and thickening of the VGE and the associated increase in local resistance progressively limit current flow, so that beyond a certain radius the plasma-dominated core can no longer be sustained [13]. This suggests two mechanisms. First, the plasma collapses locally in this central region, leading briefly to localized electrochemical polishing before plasma is reestablished as in regular PEP processes [5,13]. Second, the overall resistance increases in the central region, causing more current to flow momentarily into the splash zone, such that plasma initiation in this region becomes feasible as well [13,23]. However, because the redistributed current remains insufficient to sustain continuous plasma formation, only intermittent plasma discharges occur in the splash region. As illustrated in Figure 7, irregularities in the surface depth profiles of the splash region arise from the transient “on–off” character of these discharges. This behavior is consistent with reports on bath-type plasma electrolytic polishing systems

and highlights the critical role of current-density distribution and oscillating VGE stability in achieving process uniformity [24].

The VGE is a fundamental feature of the PEP-Jet process. Under high voltage, Joule heating in the electrolyte boundary layer raises the local temperature above the boiling point, producing a vapor layer around the electrode surface [25]. This layer acts as a dielectric barrier that limits current flow until the vapor breaks down and plasma discharge begins [26]. This plasma formation establishes a conductive channel through the previously insulating vapor phase, characterized by impact ionization and thermal excitation of vapor ion species. The resulting non-equilibrium plasma, comprising ions, and neutral particles at different temperatures, facilitates intense energy transfer to the workpiece surface through multiple mechanisms [13,27], as is the case with reactive ion species that are accelerated towards the surface [28,29]. In the jet-workpiece interaction zone the cyclic VGE formation and breakdown mechanism enables surface processing through synergistic effects: localized physical sputtering driven by momentum transfer from accelerated reactive ions together with short periods of electrochemical dissolution during local VGE breakdown [13].

Overall, these results in PEP-Jet show two coupled regimes that are more dominantly visible in the jet configuration than in PEP itself [5,30] due to the geometry-dependent increase in resistance in the splash zone: a plasma-controlled contact zone with high material removal and a diffusion-controlled splash zone with dominant electrochemical effects.

For polishing larger areas with a jet-configuration, these results suggest that successive jet passes should overlap to reduce the difference between the contact and splash zones thereby improving uniformity. Since the highest removal occurs in the approximately nozzle-diameter-wide contact zone, the overlap should ensure continuity of these high-energy regions and minimize the influence of the lower-efficiency splash zone. In summary, this work links the combined electrochemical and physical processes in PEP to the localized material response in PEP-Jet, where the central and splash zones exhibit different resistivity conditions. The agreement between simulation and experiment validates the proposed transient plasma model and provides a basis for improved process control.

5. Conclusions

This study provides new insights into the governing mechanisms of Plasma Electrolytic Polishing Jet (PEP-Jet) by correlating experimental current measurements, surface topography, and finite-element simulations. The results demonstrate the existence of two distinct polishing regimes: a plasma-dominated contact zone with an effective diameter equal to the jet diameter and an EP dominated surrounding splash zone extending to double the jet's diameter. Furthermore, the simulations support the temporal break-down of the VGE in the outer region, referred to as the splash zone, where the electrical conductivity is too low to support the plasma continuously and thus only periodically plasma ignition happens that favors strongly the electrochemical polishing. These results provide practical guidelines for optimizing jet geometry, electrolyte flow conditions, and VGE stability to improve localized plasma polishing and offer a foundation for the predictive design of future PEP-Jet processes.

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