



**International Symposium
on Electrochemical Machining
Technology**



Proceedings of the 20th INSECT 2024

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Technology 2024**

Aachen, November 18-19, 2024

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Eco-friendly electrochemical polishing via stamp flushing

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Abstract

Conventional electrochemical polishing (ECP) often relies on harmful acidic electrolytes to minimize sludge generated during anodic dissolution. This study introduces an eco-friendly ECP method developed in-house, which employs stamp flushing. In this approach, electrolyte flushing combined with the squeezing action of a vibrating tool eliminates electrolytic by-products in the inter-electrode gap (IEG). A two-dimensional numerical model was created using COM-SOL Multiphysics to examine the changing bubble fraction due to the squeezing effect, anodic dissolution, and current density (CD) distribution. The effects of various process parameters such as CD, electrolyte flow velocity, IEG, amplitude of tool vibration, and vibration speed were analyzed using response surface methodology (RSM) with a central composite design (CCD) to minimize the average surface roughness (Ra) of SS 304 components fabricated by electrochemical discharge machining (EDM). Teaching-learning-based optimization (TLBO) was then applied to minimize Ra, resulting in an experimentally verified 89.64% reduction in average surface roughness.

1 Introduction

Electrochemical polishing (ECP) is based on electrolysis, which removes the material through electrochemical dissolution. ECP enhances the corrosion

resistance properties of the component, maintaining the mechanical and metallurgical properties. The inherent attributes of ECP, such as its non-contact and non-thermal nature, distinguish ECP from other conventional polishing processes, making it indispensable for polishing high-performance and advanced metals and alloys with complex geometries. The electrolytic by-products formed during anodic dissolution are non-conductive and interfere with the electric field, causing uneven removal of material over the anode surface. Typically, the electrolytes employed in conventional ECM to minimise sludge interference and break metal oxide layer are hard to handle and are not eco-friendly.

Bannard used anionic polyacrylamides and the neutral N100 polymer as additives to reduce the flocculation time of sludge (ferric hydroxides) during the anodic dissolution of Fe in NaCl and NaNO_3 [1]. Shieh et al. suppressed oxygen evolution on the anode surface using polyethylene glycol (PEG) and sulphuric acid (H_2SO_4) as the additive during ECP of copper in 85 wt% phosphoric acid (H_3PO_4), resulting in a significant reduction of surface pitting [2]. Furuyama et al. demonstrated a finer control over current density (CD) using a moving wire ECM, where the wire is reciprocated along the surface to polish and reduced Ra value from 2 to $0.39 \mu\text{m}$ using 20 % NaNO_3 aqueous solution as electrolyte [3]. Dadi et al. developed an eco-friendly tool-based ECP using a mixture of 20 % NaNO_3 and 10 % NaCl aqueous electrolyte. They reduced the surface roughness of the atomic diffusion additive manufactured (ADAM) component by 95.92 % [4]. Though these studies have employed high-velocity electrolyte flow and pulsed current to flush out electrolytic by-products, the uniform distribution of electrolytic by-products over the electrode surfaces impacts material removal rate and surface finish.

The current study proposes a novel approach to achieve a high surface finish using eco-friendly electrolytes by incorporating stamp flushing to eliminate the interference of electrolytic by-products evolved during ECP. A multiphysics numerical model is developed to study the CD distribution, the flushing mechanism, and surface roughness reduction. The experimental setup to study stamp flushing ECP with a nano-polished flat tool is developed in-house to reduce the surface roughness of SS 304 fabricated by electrochemical discharge machining. The parameters such as current, electrolyte flow velocity, IEG, the amplitude of tool vibration, and vibration speed and their effect on reducing surface roughness are analysed using response surface methodology (RSM), and analysis of variance is implemented to identify the most influential parameters. Further, teaching-learning-based optimisation (TLBO) is applied to optimise the parameters to achieve minimum surface roughness.

2 Numerical study

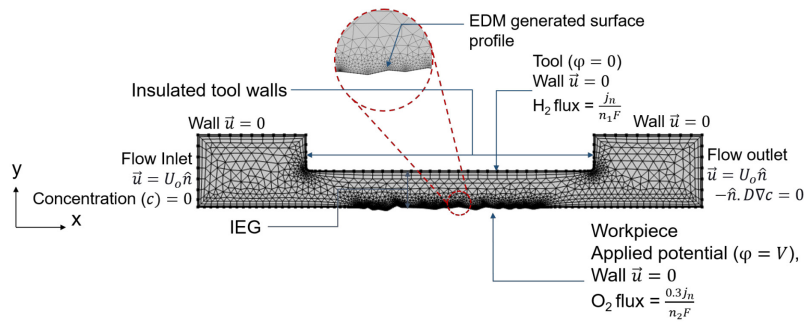


Figure 1: 2D numerical simulation domain.

A two-dimensional numerical simulation is formulated using COMSOL Multiphysics software to study the electric potential distribution, flushing method and surface roughness reduction during ECP of EDM-generated SS 304 surface. Figure 1 shows the numerical simulation domain and its boundary conditions of stamp flushing ECP with a flat electrode. The surface profile of the EDM-generated SS 304 workpiece is imported into the model to predict the final surface roughness. The anodic dissolution occurring in the polishing zone of the simulation domain comprises an electric field from the potential applied, electrolyte flow, the evolution of gases at the electrodes and anode shape evolution. The material dissolution due to the applied electric field is attained by solving the Laplace equation with its boundary conditions and Navier-stokes with continuity equation to solve the electrolyte flow in the IEG. Fick's law of diffusion, coupled with the applied potential, solves the gasses that evolved at the electrodes during ECP, and Faraday's law solves the anode shape evolution. Table 1 shows the governing equations.

Table 1: Governing equations of numerical simulation

	Governing equations
Charge conservation equation	$\nabla^2 \varphi = 0$
laminar flow	$\rho_e \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = -\nabla p + \nabla \cdot (\mu (\nabla \vec{u} + (\nabla \vec{u})^T))$
Mass transfer	$\frac{\partial C_i}{\partial t} + \nabla \cdot (C_i \vec{u} - D_i \nabla c_i + D_i N_i) = 0$
deformable mesh	$\vec{v}_n = k \times \vec{j}$

3 Experimental study

The indigenously developed stamp-flushing ECP is shown in Figure 2. It comprises a computer numerical control (CNC) system with a precision level of $\pm 10 \mu\text{m}$, a DC power supply, and an electrolyte delivery and filtration system. The CNC system facilitated precise manipulation of the 3-axis motion and vibration in the vertical axis perpendicular to the workpiece mounted in an acrylic machining chamber. The electrolyte supply unit filters and circulates the electrolyte stream in the polishing zone. A nano-polished SS 304 shaft of 6 mm diameter is used as the polishing tool. The process parameters considered for the experimental study are shown in Table 2.

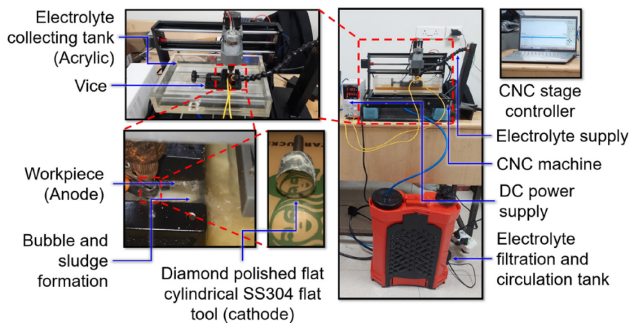


Figure 2: Stamp flushing ECP experimental setup.

The experimental studies are carried out using central composite design (CCD) where the parameters such as IEG, electrolyte flow velocity, the amplitude of vibration and vibration speed are varied, whose bounds are specified in Table 2. The average surface roughness value (R_a) is measured as the response for each experiment. Each experiment is carried out for a polishing time of 50 s.

Table 2: Experimental process parameters of stamp flushing ECP.

S. no.	Parameters	Values
1.	Current	5, 6.5, 8 A
2.	Polishing time	50 s
3.	IEG	150, 200, 250 μm
4.	Electrolyte flow velocity	4, 5, 6 m/s
5.	Vibration amplitude	50, 75, 100 μm
6.	Vibration speed	1000, 1500, 2000 mm/min

5.	Electrolyte	20% wt. NaNO_3 + 10% wt. NaCl
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A quadratic model (Equation (1)) is derived to find interactions between the prominent parameters and the response using Minitab software, where x_1 , x_2 , x_3 , x_4 & x_5 are IEG, flow velocity, current, vibration amplitude and vibration speed. The statistical significance of the fitted quadratic model is evaluated using analysis of variance (ANOVA).

$$Ra = 6.34 - 0.549x_3 - 0.001671x_5 - 0.00945x_1 - 0.0122x_4 + 0.001059x_1x_3 + 0.000405x_3x_5 \quad (1)$$

4 Results and discussion

4.1 Numerical results

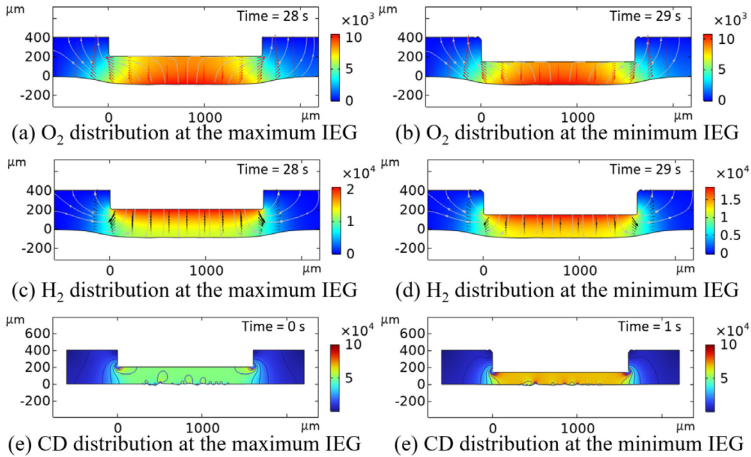


Figure 3: Numerical results on O_2 , H_2 and current density (CD) distributions at maximum and minimum IEG.

The generation of O_2 and H_2 gases at the anode and cathode, variation of their concentration in the IEG, and discharge due to the reciprocating moment of the tool are shown in Figure 3 (a)-(d). The reciprocating motion of the tool modelled in the simulation is consistent with the experimental studies. The concentration distribution of H_2 and O_2 gas evolved at the electrodes is observed to widen and move away from the IEG, representing the squeezing action due to the reciprocating motion of the tool. Further, the reciprocating motion varies the CD distribution, as shown in Figure 3 (e) & (f). Figure 4 (a) shows the reduction of surface roughness as the polishing time increases.

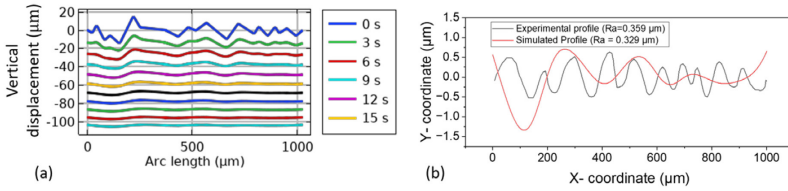


Figure 4: Numerical results (a) Surface roughness reduction with time (b) Numerical result validation.

4.2 Optimisation

ANOVA for achieving minimum surface roughness resulted in the least p-value for current, followed by vibration speed, IEG, and amplitude of tool vibration, and interactions of IEG-current and current-vibration speed of the tool were identified to be the prominent parameters at 95 % confidence. The effect of electrolyte flow velocity is insignificant as the tool vibration alters the electrolyte flow in the IEG. The optimised values of the experimental parameters optimised using TLBO are 8 A, 150 μm , 100 μm , 2000 mm/min and 5.5 m/s of current, IEG, vibration amplitude, vibration speed and flow velocity, respectively. Figure 6 shows the convergence plot of the TLBO algorithm. The minimum Ra value of 0.0603 μm is attained from the TLBO algorithm. Stamp-flushing ECP with optimised parameters resulted in Ra of 0.125 μm .

4.3 Characterisation

The surface morphology of SS 304 before and after stamp flushing ECP using optimised parameters is shown in Figure 5. Several globules, craters, voids, pockmarks and micro-cracks can be observed at 200 $\times$ on the EDM surface. The high-temperature plasma generated during continuous micro-discharges melts and vaporises locally over the workpiece surface, leading to crater formation. The unremoved material resolidifies due to rapid quenching by the dielectric forms as globules and recast layer. Micro-voids on the Electrical Discharge Machining (EDM) surface arise from the expulsion of entrapped gas bubbles during the solidification process of molten material. Figure 5 reveals that the surface polished by stamp flushing ECP is free from globules, micro-cracks, voids and pockmarks. The Ra value has reduced from 3.8 μm to 0.125 μm using stamp flushing ECP with optimised parameters from the TLBO algorithm.

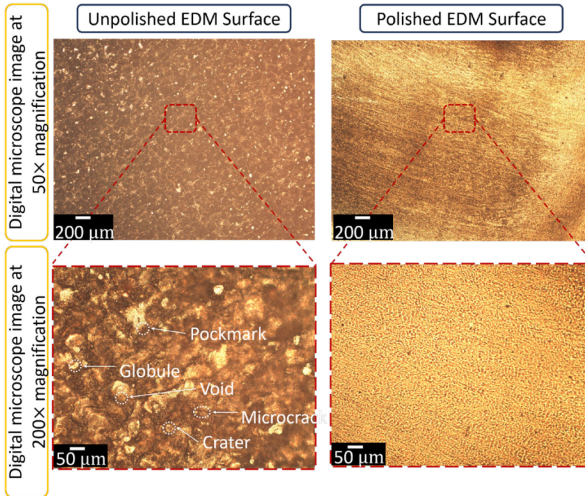


Figure 5: Surface morphology before and after stamp flushing ECP of EDM generated surface.

The numerical surface profile of the EDM surface after stamp flushing ECP is compared with the experimental results using identical polishing parameters to validate the numerical simulation results. A close match is observed in the surface profile and the Ra value, as shown in Figure 4 (b).

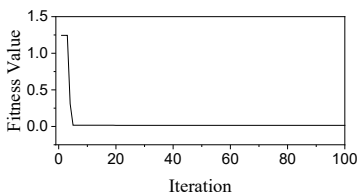


Figure 6: Convergence plot of TLBO algorithm.

5 Conclusion

The current study shows the effectiveness of the stamp-flushing ECP in reducing the surface roughness of the SS 304 component fabricated by EDM. The novel approach developed is studied numerically and experimentally. The squeezing effect of the vibrating tool is investigated using numerical simulation, and the Ra values are compared experimentally with and without vibration. CCD is used to conduct experimental analysis, and the most influential parameters are deduced using ANOVA. A quadratic model is fitted based on the

influence of parameters and their interactions on the surface roughness. The parameters are optimised to achieve minimum surface roughness using the TLBO algorithm. The findings are summarised as follows:

- The numerical results showed a variation in the concentration of gases evolved at the electrodes due to the squeezing action by the vibrating tool. Higher CD at the peak points than the valleys indicates the process's effectiveness in levelling the undulation over the anode surface.
- The constant current applied at the electrodes is deduced as the most influential parameter, followed by vibration speed, IEG, amplitude of tool vibration, and interaction between IEG-current and current-vibration speed.
- The surface roughness reduction achieved without vibration was 91.42 %, whereas, with stamp flushing ECP, the surface roughness the surface roughness has reduced by 96.71 %.
- The EDM surface defects such as globules, micro-cracks, voids and pockmarks are eliminated by polishing the surface using stamp flushing ECP.

The conclusion of this study suggests stamp flushing ECP as an effective process to achieve a high surface finish using eco-friendly electrolytes.

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