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EFFECT OF ELECTROCHEMICAL PROCESS PARAMETERS ON THE HASTELLOY C-276 ALLOY FOR MACHINING SPEED AND SURFACE-CORROSION FACTOR

VPLIV PARAMETROV ELEKTROKEMIJSKIH PROCESOV NA SUPERZLITINO HASTELLOY C-276 GLEDE NA HITROST MEHANSKE OBDELAVE IN KOROZIJO POVRŠINE

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Electrochemical micromachining (ECMM) is a well know for manufacturing hard-to-cut materials, e.g., nickel-based alloys, titanium alloys and metal-matrix composites. For this reason it finds application in aerospace, automobile and biomedical industries. In this research Hastelloy C-276 is used as a workpiece and stainless-steel electrode coated with polytetrafluoroethylene (PTFE) to avoid stray current. The effect of process parameters such as voltage, duty cycle and electrolyte concentration on the machining speed and the surface-corrosion factor were studied. The range of 9–11 V has an impact on the machining speed. The electrolyte concentration range of 25–35 g/L shows a linear increase in the machining speed and the surface-corrosion factor is found to be highest at 1.1449 for an electrolyte concentration of 15g/L. The surface roughness depth profile depicts the values of Rz, Rt, Ra are 16.3 μm, 99.1 μm and 1.90 μm, and 15.4 μm, 50.6 μm and 1.49 μm, respectively.

Keywords: Hastelloy C-276, polytetrafluoroethylene, surface-corrosion factor, stray current, coating

Elektrokemijska mehanska obdelava površine (ECMM; angl.: Electrochemical micromachining) je zelo dobro znana obdelava za rezanje trdih materialov kot so zlitine na osnovi niklja, zlitine na osnovi titana in kompoziti s kovinsko osnovo. Zato ECMM lahko najdemo v aplikacijah za letalsko, avtomobilsko in biomedicinsko industrijo. V tem članku avtorji opisujejo raziskavo pri kateri so uporabili preizkušance iz nikljeve proti koroziji odporne superzlitine vrste Hastelloy C-276 in elektrodo iz nerjavnega jekla prevlečeno z politetrafluoroetilenom (PTFE), da bi se izognili zablodelim električnim tokovom (angl.: stray current). Avtorji so študirali vpliv procesnih parametrov, kot so: električna napetost, čas obdelave in koncentracija elektrolita na hitrost mehanske obdelave ter faktorje, ki vplivajo na površinsko korozijo. Avtorji v članku ugotavljajo, da ima napetost v območju med 9 V in 11 V pomemben vpliv na hitrost obdelave. V območju koncentracije elektrolita med 25 g/L in 35 g/L so avtorji ugotovili linearno naraščanje hitrosti obdelave in ugotovili so, da je faktor površinske korozije višji od 1,1449 pri koncentraciji elektrolita 15 g/L. Ugotovljene vrednosti globine površinske hrapavosti so bile za Rz, Rt in Ra 16,3 μm, 99,1 μm in 1,90 μm oziroma 15,4 μm, 50,6 μm in 1,49 μm.

Ključne besede: zlitina vrste Hastelloy C-276, elektrokemijska mikromehanska obdelava, politetrafluoroetilen, factor površinske korozije, raztreseni (zablodeli) električni tokovi, oplaščenje

1 INTRODUCTION

Electrochemical micromachining (ECMM) is a non-traditional machining method for manufacturing parts with good surface quality and production rate. In ECMM the tool (cathode) and workpiece (anode) are kept in an electrolyte bath and while the application of the potential difference across the electrodes material removal occurs at the workpiece. By controlling the various factors such as electrical parameters and electrolyte concentration, controlled material removal happens in the workpicece. ECMM finds application in various fields ranging from aerospace to biomedical engineering. Research on ECMM in past decades focused on improving the production rate, accuracy and surface property. Venugopal et al.[1] used a polytetrafluoroethylene (PTFE)-coated electrode to improve the machining rate and overcut. They reported that the electrolyte concentration shows the major contribution for improving the conicity of the micro-hole. VinodKumaar et al.[2] used copper powder in the electrolyte along with stirring mechanism to improve the machining rate and the overcut. The use of a suspended electrolyte with stirring effect produces higher MRR and moderate overcut.Venugopal et al.[3] used a magnetic field effect and graphite electrode and reported that graphite and magnetic electrodes resulted in 11.9 % and 3.41 % reduced OC, compared to a stainless-steel tool. Rajan et al.[4] machined metal-matrix composites using ECMM and reported that a metal-matrix composite with 10% B_4C shows good machinability. Thanigaivelan et al.[5] reported the impact of tool-tip shape, i.e., flat shape, truncated and conical shape, on the machining rate and

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Table 1: Composition of Hastelloy C-276 (*w*/%)[7]

Ni	Cr	Mo	Fe	W	Mn	Cu	C	Si	Co	V
57 balance	16	16	5	4	<1	0.5	<0.01	≤0.08	≤2.5	≤0.35

Table 2: Tabulated values of ECMM factors and performance measures

Expt. No	Voltage (V)	Duty Cycle (%)	Electrolyte Concentration (g/L)	Machining Speed (µm/sec)	Surface Corrosion Factor
1	7	90	35	0.1583	1.1231
2	8	90	35	0.1759	1.0234
3	9	90	35	0.2111	0.9045
4	10	90	35	0.2879	1.0848
5	11	90	35	0.3725	1.0602
6	11	50	35	0.1624	1.1179
7	11	60	35	0.1979	1.0645
8	11	70	35	0.2111	1.0714
9	11	80	35	0.2639	1.0595
10	11	90	35	0.3167	1.0759
11	11	90	15	0.1583	1.1449
12	11	90	20	0.1810	1.1312
13	11	90	25	0.2262	1.0625
14	11	90	30	0.3167	1.0825
15	11	90	35	0.4222	1.0988

Table 3: Fixed parameters

Constant parameters	Thickness of workpiece	Electrode diameter	Frequency	Volume of Electrolyte
Values	380 µm	484 µm	50 Hz	1 L

overcut. They concluded that the tool-tip shape has an impact on machining rate and overcut. Kumarasamy et al.[6] used a variety of electrolytes, i.e., sodium nitrate, sodium chloride and mix of all these electrolytes with citric acid to improve the material removal rate, overcut, conicity and circular holes. They reported that the mixed electrolyte improves all these output performances. Panigrahiet al.[7] machined Hastelloy C -276 using ECMM and noticed broken grains and inflated grain boundaries with a spreading crack due to the stray current corrosion. Gobinath et al.[8] showed that electrolytes mixed with nanoparticles play an important role in ECMM with an increase in MRR and a decrease in cross-section and surface roughness at the optimized parameter setting level with a processing voltage of 7 V and an electrolyte concentration of 5 g/L and a nanopowder suspension of 5 g/L. Liu et al.[9] reviewed the ECMM for metallic workpieces. They have studied the effect of electrodes, electrolytes on the surface properties of the metallic workpieces. They concluded that these parameters have an impact on the surface quality of metals machined in ECMM. Thangamani et al.[10] studied the influence of three electrolytes, i.e., sodium-chloride-based electrolytes, on a titanium alloy. The study revealed that the combination of sodium chloride and citric acid achieves the greatest cross-section and roundness. Better conicity were obtained from sodium chloride and citric acid compared to the other electrolytes. The combination of sodium chloride and glycerol gave a better treated surface due to the chelating effect of glycerol. Researchers enhanced the material removal rate and overcut and only few have concentrated on evaluating the corrosion and pitting on the machined surface. The corrosion formation on the surface of the workpiece affects the surface quality and weakens the metal, but it also generates a bell mouth profile. Hence, in this research an experiment is planned to evaluate the surface-corrosion factor for the Hastelloy C-276.

2 EXPERIMENTAL PART

Figure 1 depicts the ECMM setup used for machining the workpiece of Hastelloy C-274. **Table 1** presents the composition of Hastelloy C-276. This alloy has excellent mechanical and corrosion resistance properties and is used in high-temperature and high-pressure environments. The electrode made of stainless steel is coated with polytetrafluoroethylene (PTFE) to prevent electric flux escaping from the circumference of the electrode.[1] The PTFE has good thermal and chemical inertness along with electrical insulation characteristics. **Figure 2** shows the tool coated with PTFE. The workpiece is given with positive charges and the cathode is connected with the negative charges and sodium nitrate electrolyte ($NaNO_3$) is used to bridge the two electrodes. The $NaNO_3$ electrolyte is prepared using 1 liter of distilled water and thoroughly mixed with different weights of salts. The ECMM setup has basic elements for electrolyte recirculation, a tool forwarding attachment and a pulsed supply system. The input parameters and levels

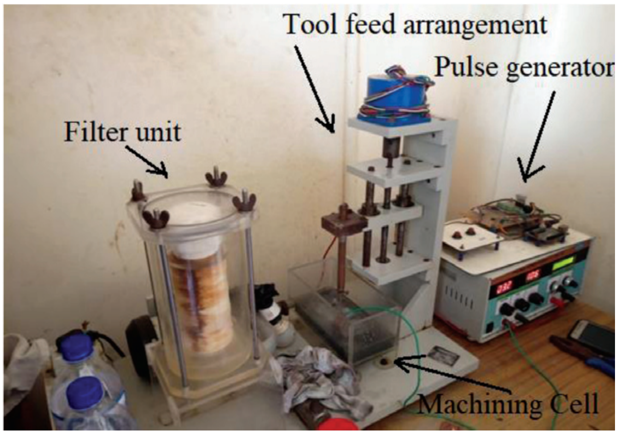

Figure 1: ECMM Cell

are selected based on the previous experiments, i.e., voltage, duty cycle and electrolyte concentration and output performances are machining speed and surface corrosion factor.[11] **Table 2** shows the parameters and levels and the output performance. The machining speed is evaluated by measuring the thickness of the workpiece using the micrometer and dividing the same value using the machining time in seconds. The machining time is the time taken to complete the micro-hole. The evolution of hydrogen bubbles beneath the workpiece from the electrode ensures the completion of the micro-hole.[12] The surface corrosion factor is measured using the optical microscope image which is the ratio of Dmax to Dmin. Dmax is the length of the surface with corrosion/pitting and Dmin is the length of the micro-hole.[13]

3 RESULTS

The effect of voltage on the machining speed and surface-corrosion factor is shown in **Figure 3**. It can be perceived from the graph that the machining speed increases with voltage. The input is varied between 7 V and 11 V, while the increase in voltage increases the electrochemical reaction. The increase in voltage enhances the current density required for the machining. As per Faraday's law of electrolysis, the dissolution efficiency depends on the applied voltage between the electrodes. The linear increase in machining speed is witnessed for the range of 9 V to 11 V. At a higher voltage the migration of ions from the anode is larger, attributed to a higher machining speed. The migration of ions from the anode depends on the electric potential and electric gradient. Moreover, the formation of the double layer at the anode due to polarization increases the dissolution.[14] The PTFE-coated electrode prevents any stray current occurring at the circumference of the electrode and the anode and cathode gap plays an important role in the dissolution process. If the distance between the anode and cathode is shorter than the double layer, the capacitance charging will be quicker attributing for a highly localized dissolution.

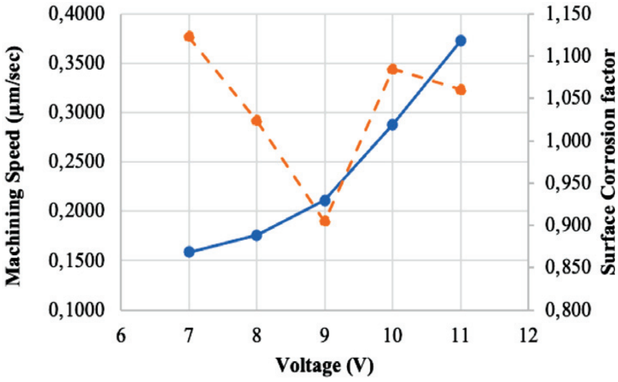

Figure 3: Voltage vs machining speed and surface-corrosion factor

The surface-corrosion factor decreases with an increase in the voltage level and further increases, as presented in **Figure 4.** In the ECMM process, although the tool electrode is coated with PTFE, the straying current from the tool tip forms the surface pitting/corrosion on the anode surface. For the parameter combination of 7 V, 90 % duty cycle, 35 g/L electrolyte concentration, the surface-corrosion factor is 1.1231. At 90 % duty cycle the pulse on time is on live for more time and stray cur-

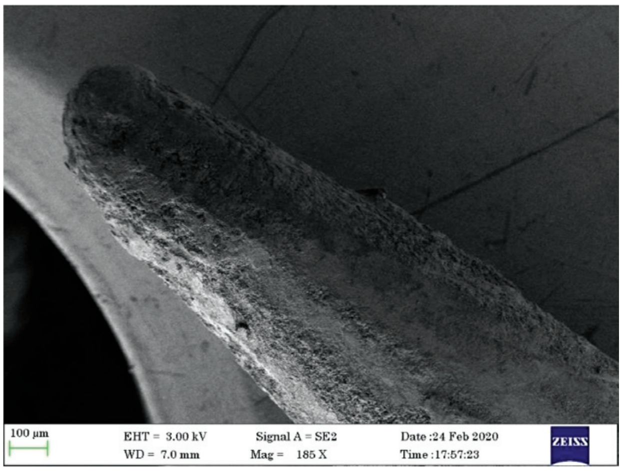

Figure 2: PTFE-coated tool

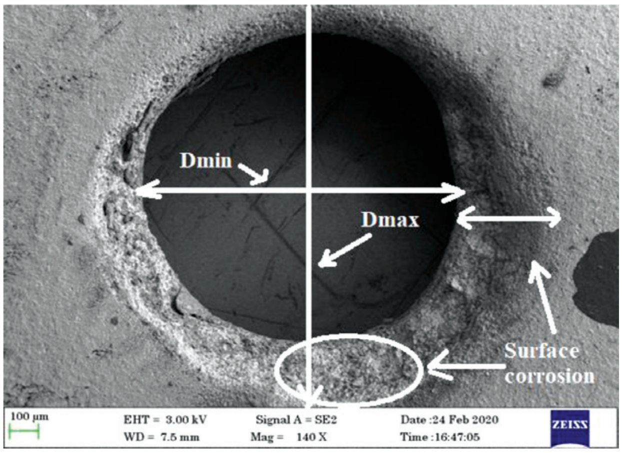

Figure 4: Micro-hole with surface corrosion

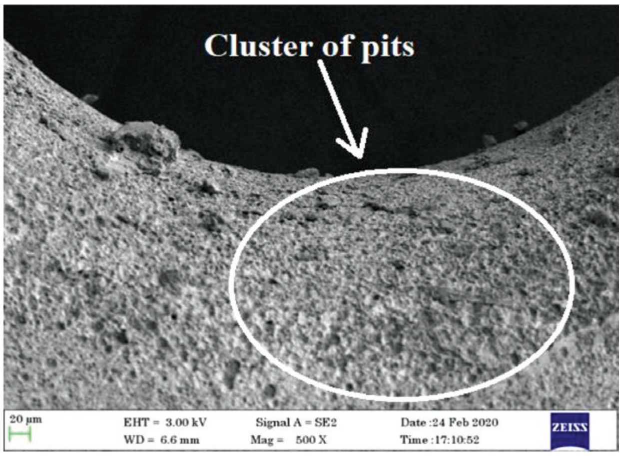

Figure 6: Micro-hole surface with cluster of corrosion/pitting

rent flux from the tip creates the surface corrosion on the top surface of the workpiece. **Figure 5** shows the micro-hole with the surface corrosion/pitting. The surface pitting arises due to the formation of a localized electrochemical cell on the surface of the Hastelloy C-276. The localized electrochemical cell will split into anodic and cathodic zones in which the breaking of the oxide layer and the underlying metal act as an anode and surface of the hastelloy C-276 act as a cathode.[15] This phenomenon leads to the formation of pits on the micro-hole circumference. The clusters of pits are shown in **Figure 6**. T he formation of tiny pits is caused by the repetitive electric force, and collapsing of hydrogen bubbles in the machining area. The hydrogen bubbles are evolved by the cathode during the electrolysis.

The effect of duty cycle on the machining speed and surface-corrosion factor is depicted in **Figure 7**. The machining speed shows an increasing trend with an increase in the duty cycle. The linear increase in machining speed is witnessed for the duty cycle range of 70 % to 80 %. The duty cycle is the ratio of the pulse-on time to the total time (Pulse-on time + Pulse-off time) and the 70 % duty cycle contributes a good quantity of the current density required for machining. A further increase in the duty cycle to 90 % the pulse-off time reduces and the pulse-on time increases to the maximum value, and this

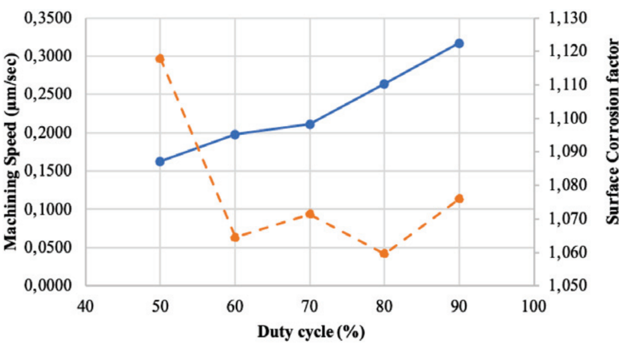

Figure 7: Duty cycle vs machining speed and surface-corrosion factor

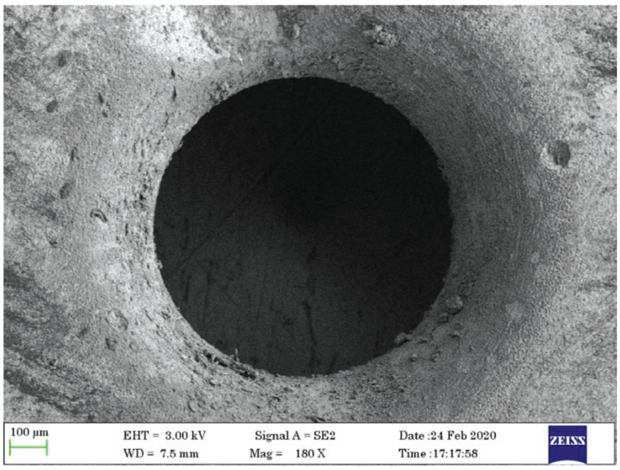

Figure 8: Micro-hole with less corrosion/pitting

high duration of pulse-on current in the electrode attributes for the high machining speed.

The surface-corrosion factor is found to decrease with the increase in the duty cycle. At 11 V, 50 % duty cycle, 35 g/L electrolyte concentration the surface-corrosion factor is high due to the longer pulse-off time. During the lower duty cycle the pulse-on time is less and more time is required for machining. Hence, at a lower duty cycle the surface corrosion is 1.1179 and further reduces to 1.0645 for 60 % duty cycle. At 11 V, 90 % duty cycle and 35 g/L electrolyte concentration the surface-corrosion factor is less due to the fact at higher level of input parameters the dissolution rate is faster and hence the workpiece-surface exposure time to the stray current is less, leading to less corrosion/pitting on the circumference of the hole, as shown in **Figure 8**.

The effect of electrolyte concentration on the machining speed and surface-corrosion factor is shown in **Figure 9**. For machining the Hastelloy C-276, the passivating electrolyte $NaNO_3$ is used. The formation of corrosion/pitting on the surface of the workpiece depends on the stray current from the electrode. In the ECMM machining process the current density depends on the conductivity of the electrolyte and the intensity of the

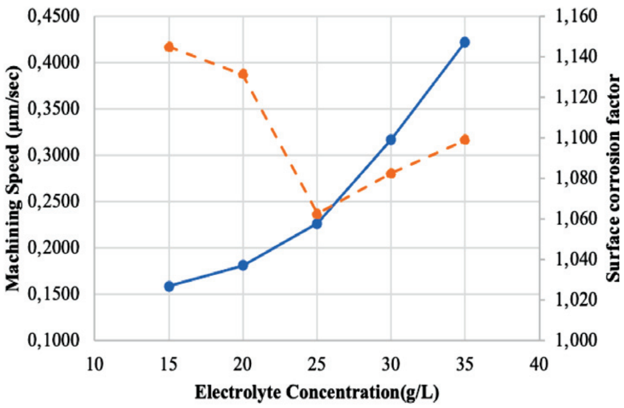

Figure 9: Electrolyte concentration vs machining speed and surface-corrosion factor

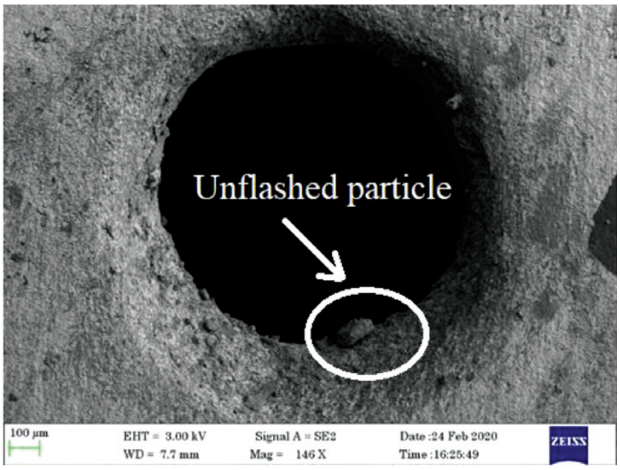

Figure 10: Micro hole with unflashed debris

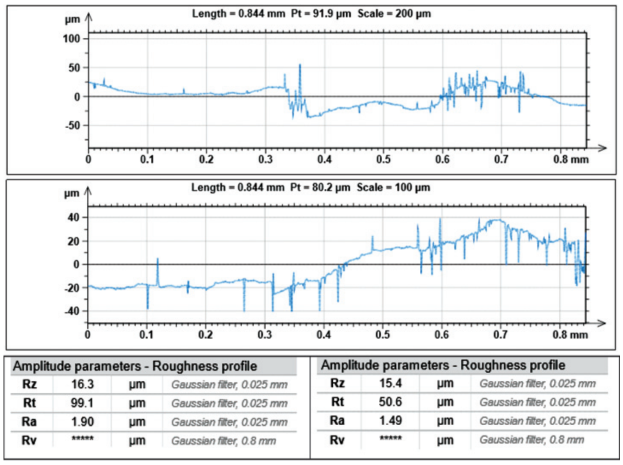

Figure 12: Depth profile of the corrosion-affected surface

electric field.[16] The electrical conductivity again depends on the temperature of the electrolyte and quantity of dissolution product in the electrolyte. At 11 V, 90 % duty cycle and 15 g/L of electrolyte concentration the number of ions in 1 litre of distilled water is responsible for less removal of material from the workpiece. A further progressive increase in electrolyte concentration increases the machining rate, as depicted in **Figure 9**. The machining speed linearly increases with electrolyte concentration range of 25 g/L to 35 g/L. The surface corrosion factor found to 1.1449 for the experiment combination, i.e., 11 V, 90% duty cycle, 15 g/L. A further increase in the electrolyte concentration from 25 g/L to 35 g/L the surface corrosion is found to be 1.0625, 1.0825 and 1.0988, respectively, which is less than the electrolyte concentration range of 15 g/L to 20 g/L. The generation of the reaction product will be high at a higher concentration of electrolytes and moreover the bursting of gas bubbles diminishes the stray current pitting. **Figure 10** shows the micro-hole with un-flushed debris. The proper flushing of debris ensures good quality in the ECMM.

Figure 11 shows the surface profilograph of the corrosion-affected zone. The surface roughness depth profile shown in **Figure 12** depicts the values of Rz, Rt, Ra as 16.3 µm, 99.1 µm and 1.90 µm, respectively, and on repeating the same the lowest surface roughness was obtained as 15.4 µm, 50.6 µm and 1.49 µm. The 3D surface file shown in **Figure 13** shows the surface roughness values of 0.844 mm, 0.844 mm and 176 µm along the X, Y and Z directions.

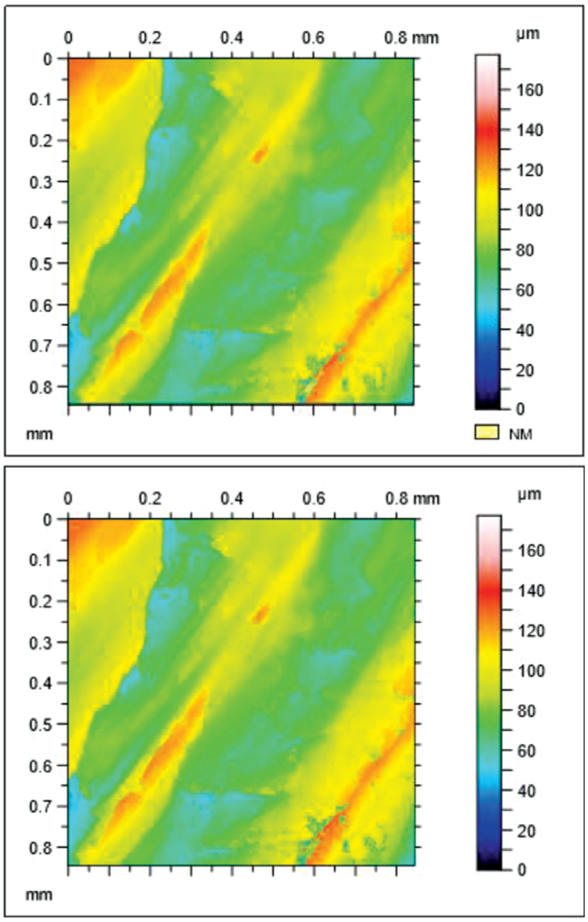

Figure 11: Surface profile graph of corrosion zone

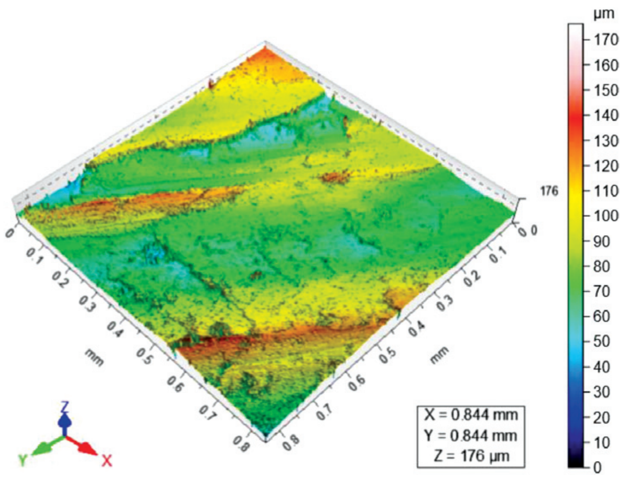

Figure 13: 3D surface profile of the corrosion-affected zone

4 CONCLUSIONS

The PTFE-coated electrode is used in ECMM to understand the effect of the process parameters on the machining speed and the surface-corrosion factor. The effect of voltage, duty cycle and electrolyte concentration on the above was studied. The voltage range of 9–11 V has an impact on the machining speed. The surface corrosion was found to be 1.1231, which is the third-highest value for the parameter combination of 7 V, 90 % duty cycle and 35 g/L electrolyte concentration. The surface-corrosion factor decreases with an increase in the voltage. Among the conducted experiments, the 9 V, 90 % duty cycle, 35g/L combination shows lowest surface-corrosion factor of 0.9045. The duty-cycle range of 70–90 % has an influence on the machining speed. The electrolyte concentration range of 25–35 g/L shows a linear increase in the machining speed and the surface-corrosion factor is found to be highest of 1.1449 and second highest of 1.1312 for the electrolyte concentrations of 15 g/L and 20 g/L, respectively. The surface-roughness, depth-profile values of Rz, Rt, Ra for the corrosion-affected zone are 5.4 µm, 50.6 µm and 1.49 µm.

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