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SCIENTIFIC PAPER

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EFFECT OF DIFFERENT ELECTROLYTES ON ELECTROCHEMICAL MICRO-MACHINING OF SS 316L

Article Highlights

- This paper aims to fabricate the drilled micro-holes on SS 316L through the ECMM process
- Tartaric acid, citric acid, and mixed electrolyte are used for conducting the experiments
- MRR and overcut are considered to measure the performance of the machining process
- FESEM analysis is conducted to see the influence of the electrolyte on the machining surface
- Mixed electrolyte outperforms MRR and overcut than the other electrolytes

Abstract

The use of stainless steel 316L (SS 316L) in the medical, marine, aerospace, bio-medical, and automobile sectors increases rapidly. Electrochemical micro-machining (ECMM) is the appropriate method for machining SS 316L due to its burr-free machining surface, no residual stress, and high precision. However, some limitations are found in using strong electrolytes, such as HCl, H_2SO_4, KOH, $NaNO_3$, and NaCl, which reportedly face difficulties in disposing to the environment and handling issues. Hence, this paper addresses overcoming the disadvantages encountered in the ECMM process when using strong electrolytes to machine SS 316L. Therefore, different organic electrolytes such as tartaric acid ($C_4H_6O_6$), citric acid ($C_6H_8O_7$), and a combination of tartaric and citric acid (mixed electrolyte) are considered to select the best electrolyte. Process parameters like machining voltage, duty cycle, and electrolyte concentration are included in determining machining performance. The performance of ECMM is evaluated using material removal rate (MRR) and overcut. The overcut of tartaric acid electrolyte is 179% less than mixed electrolyte for the parameter combination of 12 g/l, 11 V, and 85%. On the other hand, the mixed electrolyte shows 114.2% higher MRR than the tartaric acid electrolyte for the parameter solutions of 25%, 11 V, and 20 g/l. Furthermore, the citric acid electrolyte shows the second-lowest overcut and higher MRR in all aspects of machining performance. Field emission scanning electron microscope (FESEM) studies are carried out to realize the effect of electrolytes on the machining surface.

Keywords: micro-machining, weak electrolytes, electrochemical, SS 316L, MRR, overcut.

In non-traditional machining methods, several machining techniques are available for machining SS 316L material, like ultrasonic machining, laser beam machining, electron beam machining process, and electro-discharge machining. Even though those methods are expensive, they have a lower surface quality due to the thermal application on the machining zone [1]. The ECMM process is one of the most prominent and most suitable techniques for machining materials like SS [2]. Since the ECMM method encom-

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passes characteristics such as burr-free machining surfaces, no heat is produced during the machining process, tool and workpiece wear are less and high accuracy [3,4]. However, because of technological growth and demand for micro products, ECMM needs to be updated in all aspects of machining. Also, every material finds a unique character based on the particles mixed up, demonstrated by its mechanical strength [5,6]. In the same way, materials could be dissolute by electrochemical reactions based on the type of electrolyte used [7]. Therefore, many researchers have carried out experiments with different electrolytes and their modifications in the last decade. Moreover, strong electrolytes contribute to a larger overcut and more material removal from the previous literature. Still, at the same time, it also causes hazards to the environment and operator. Therefore, to compensate for the drawbacks faced in using strong electrolytes, this paper proposes to use weak electrolytes for the machining of SS 316L.

In line with that, Thangamani *et al.* [8] used different electrolytes such as sodium nitrate ($NaNO_3$), plain sodium chloride (NaCl), and NaCl with citric acid as a mixed electrolyte for the ECMM of titanium alloy. They found that plain NaCl and $NaNO_3$ electrolytes had a higher MRR, while mixed NaCl and citric acid electrolytes had a lower overcut and taper angle. Patel *et al.* [9] adopted the novel setup with $NaNO_3$ electrolyte to atomize its molecular mist in the ECMM of SS 304 work material. They mentioned that the atomized flushing technique improves the 52% machining rate and reduces the overcut by about 13% with 6 V machining voltage. Also, the consumption of electrolytes for the ECMM process is reduced significantly. Kumarasamy *et al.* [10] used various electrolytes for the ECMM of haste alloy, including NaCl, $NaNO_3$, and a mixture of these two with citric acid electrolyte. They optimized the process parameters using the Taguchi method with the outcome of surface roughness, MRR, taper angle of the micro-hole and overcut. They also mentioned that the mixed electrolyte shows a significant improvement in the results of the ECMM.

In the ECM process, Zhan *et al.* [11] applied pressurized gas to the surroundings of the tool electrode with varying parameters. They noted that pressurized gas prevents stray current effects on the workpiece, which significantly improves the precision of micro-holes. Also, this gas supply acts as tool insulation and improves the electrolyte localization effect due to the conductivity improvements. As a result, the surface roughness of the micro-hole improved about 52 times higher than the typical electrolyte. Soundarrajan *et al.* [12] mixed the hot and dry air in the citric acid electrolyte for machining copper work material. They reported that hot air energies the electrolyte more, which increases the machining rate by 2 times better than the dry air mixed electrolyte. The dissolution products of copper work material act as an insulation layer for the tool electrode and prevent the stray current effect on the work surface. This phenomenon improves the taper angle of the micro-hole significantly. Mouliprasanth *et al.* [13] attempted to use the ECMM process with passivating and non-passivating electrolytes for shape memory alloys. They optimized the process parameters through the Taguchi technique over the outcomes of MRR, taper angle, and overcut. Subburam *et al.* [14] optimized the process parameters of ECMM with citric acid electrolyte for SS 304 material. They applied the grey relational analysis optimization technique to find the optimal electrolyte solution and process parameters for the ECMM method. It was also suggested that the parameter combination of 20g/l electrolyte concentration, 12 V machining voltage, and 15 ms pulse on-time produces the highest machining rate and less overcut.

Soundarrajan *et al.* [15] mixed hydrochloric acid with $NaNO_3$ electrolyte for machining the aluminum metal matrix composite. First, they compared the results of the acidified electrolyte with those of the non-acidified electrolyte. They found that the acidified electrolyte produces 3.5 times higher MRR than the non-acidified electrolyte for the parameter combination of 15 V, 30 g/l, and 90%. Next, Guo *et al.* [16] tried the ethylene glycol-based $NaNO_3$ electrolyte for machining the zirconium metallic glass in the ECM process. They noted good stray current protection in the machining zone compared to the water-based electrolyte, which causes very little pitting correction on the machining surface. Finally, Ao *et al.* [17] tried a 20% ethanol mixed ethylene glycol-based NaCl electrolyte in the ECMM of a shape memory alloy. They reported that 20% of ethanol mixed with electrolyte reduces the oxide layer formation that causes the smooth machining roughness. At the same time, machining precision is more affected when the ethanol percentage is exceeded.

Vinod Kumaar *et al.* [18] adopted the magnets in the citric acid electrolyte using the ECMM process to machine SS 316L work material. A magnetic field induces the molecules present in the electrolyte, which causes a higher electrical conductance and a twice better machining rate than the plain citric acid electrolyte. Soundarrajan *et al.* [19] heated the $NaNO_3$ electrolyte using ultraviolet rays in the ECMM of copper material. They reported that the 2.56 times higher MRR is achieved due to the heat of the electrolyte workpiece getting softened and the UV rays of short wavelength, which causes the 2.56 higher MRR than the infrared heated electrolyte. However, there was a significant overcut on the micro-holes due to electrolyte energy. Chen *et al.* [20] created the micro dimples on titanium alloy with the ECMM process using $NaNO_3$ electrolyte. They noted that continuous oxide layer formation causes stray current pitting on the machining surface. They also suggested process parameters for better machining performance, such as 24 V, 100 Hz frequency, and 10% duty cycle. Raj Keerthi *et al.* [21] used the $NaNO_3$ electrolyte for the Co-Ni-Cr-W superalloy in the ECMM process using two different tools: a fabricated hollow tool and a typical cylindrical tool. They compared the results, such as circularity, surface roughness, and MRR, of the hollow tool with those of the usual tool using $NaNO_3$ electrolyte. The results show that 2% MRR increased and 24% overcut was reduced with the hollow tool compared to the standard tool.

Vinod Kumaar *et al.* [22] studied the effects of using the oxalic acid electrolyte for machining SS 316L work material in the ECMM process. They reported that oxalic acid enhances the MRR by 2.5 times and reduces the overcut significantly. Wang *et al.* [23] proposed the inner wall modified nozzle for electrolyte supply in the machining zone. They noted stray current was less in the machining zone due to the turbulated electrolyte, which increases the machining accuracy on the nickel work material. Kunar *et al.* [24] tried various electrolytes such as NaCl and $NaNO_3$ and the combinations of these two electrolytes for SS 304 materials in the ECMM process. They discovered that a combined electrolyte of NaCl and $NaNO_3$ outperforms the plain electrolyte in terms of machining performance. The above literature clarifies that researchers have employed various electrolytes to enhance the machining performance of ECMM. Although different electrolytes are commercially available, the cost of machining on a large scale is prohibitively expensive. Strong electrolytes, such as acid-based and alkaline-based electrolytes, continue to face significant challenges in terms of environmental measures, cost, and human safety [25]. Some research findings explored the results of ECMM process parameters with organic electrolytes, whereas there is no evidence for SS 316L with an organic electrolyte. Hence, in this work, commercially available, natural, weak, and less expensive electrolytes such as citric acid, tartaric acid, and mixed acid are used as electrolytes. The design of experiments is planned, including the machining parameters, such as machining voltage, duty cycle, and electrolyte concentration. FESEM analyses are taken to see the effect of the electrolyte on micro-holes and the surface.

The proposed chemical reaction of the electrolyte

Citric acid is one of the organic acids obtained from natural plants such as lemons and oranges. Usually, citric acids are used in industries like metal polishing, food, paint manufacturing, and chemicals due to their affinity nature. Also, this is one of the best chelating agents to clean the SS work materials [18]. Hence, in this experiment, citric acid is considered the electrolyte. In the ECMM process, materials dissolve on the workpiece by applying electric potentials between the tool and work. Due to these potential changes in the electrolyte, a reaction occurs in the machining process. Citric acid is a triprotic or tricarboxylic acid group of acids that can be subjected to equation (2) and separated by distilled water (1). Hence, the citric acid could be dissolved in distilled water and leave one hydrogen present in the equation (3). This hydrogen forms the hydronium ions when reacted with oxygen in distilled water.

$$(H_2O) \rightarrow (H^+) + (OH^-) \tag{1}$$

$$(C_6H_8O_7) \rightarrow (C_6H_5O_7)^{3-} + 3H^+ \tag{2}$$

$$(C_6H_8O_7) + (H_2O) \rightarrow (C_6H_5O_7)^{3-} + (H_3O^+) \tag{3}$$

Tartaric acid is one of the diprotic or two carboxylic groups of acids and weak organic acids extracted from fruits such as grapes, bananas, tamarinds, etc. The reactions of tartaric acid when mixed with distilled water are present in the following equations. Equations (4) and (3) exhibit the reaction of tartaric acid and distilled water together. As per the equation (5), hydrogen from the tartaric acid joins with oxygen and forms the hydronium ion (H_3O^+):

$$(C_4H_6O_6) \rightarrow (C_4H_4O_6)^{2-} + (2H^+) \tag{4}$$

$$(C_4H_6O_6) + (H_2O) \rightarrow (C_4H_4O_6)^{2-} + (H_3O^+) \tag{5}$$

Mixing citric acid and tartaric acid may undergo the following reaction, represented in equation (6). Citrate anions $(C_4H_4O_6)^{2-}$ and D-tartrate anions $(C_6H_5O_7)^3$ are formed when both acids mix. Also, the hydronium ion is created, which is defined in the equation:

$$(C_6H_8O_7) + (C_4H_6O_6) + (H_2O) \rightarrow (C_6H_5O_7)^{3-} + (C_4H_4O_6)^{2-} + (H_3O^+) \tag{6}$$

Metal oxidation occurs on the SS 316L work piece. In all three acids (citric, tartaric, and combination of citric and tartaric acid), the following reaction may occur, which is presented in equation (8).

$$(Fe) \rightarrow Fe^{2+} + 2e^- \tag{7}$$

$$(C_6H_5O_7)^{3-}+(C_4H_4O_6)^{2-}+Fe^{2+}\rightarrow Fe_3(C_6H_5O_7)_2(C_4H_4O_6) \quad (8)$$

The ferrous metal ion reacts with hydrogen in the electrolyte and forms ferrous citrate $Fe_3(C_6H_5O_7)$ and tartrate. This formation is termed 'sludge' in the electrolyte and acts as a conductive bridge.

In the cathode, hydrogen bubbles are released from the electrode while machining.

$$2H^{+}+2e^{-}\rightarrow H_2\uparrow \quad (9)$$

MATERIAL AND METHODS

The ECMM setup is represented in Figure 1, which was developed indigenously for conducting the experiments. The setup comprises various parts like an electrolyte tank, tool feed control system, filter, and pulse rectifier. The experiments were conducted with a SS 316L workpiece with a 500 µm thickness and employed as an anode. The pulse frequency is set at 100 Hz, and the total pulse width is 10 milliseconds. The tool electrode of size φ 460 µm is employed as a cathode and insulated using epoxy resin, preventing stray current in the machining zone. The constant tool feed rate is applied while machining the material. The performance of ECMM has been measured with an assessment of MRR and overcut. Through-hole with respect to the machining time is considered for MRR, and differences in micro-hole diameter and tool diameter are considered for the overcut. An optical microscope is used to find out the diameter of the micro-hole. The natural phenomenon, namely the triprotic property of citric acid, prevents the formation of unwanted sludge (insoluble) in the machining zone, thereby maintaining the electrolyte character until the end of the experiment [12]. Also, the effects of other weak electrolytes such as citric acid, tartaric acid, and the mixing of citric and tartaric acid were considered for the experiments. The experiment plan is based on varying one parameter at a time, keeping all other factors constant. The experimental results are presented in Table 1.

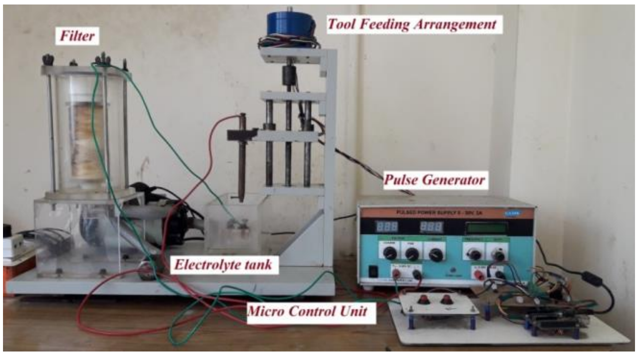


Figure 1. Experimental arrangement of ECMM.

The research on mixed electrolytes for ECMM provided the best solution due to the atom migrations between the electrolytes. Therefore, to obtain the best machining performance on ECMM, citric acid and tartaric acids are mixed in equal proportion and considered an electrolyte for the experiment. The preparation of mixed acid electrolyte combinations is presented in Table 2. In addition, other electrolytes such as tartaric and citric acid are used as they are in their regular form. The conductivity of ions in the electrolyte is initially determined using the following equation: = L/RWt, where L is the distance between the electrodes, R is the resistance of the electrolyte solution offered between the two electrodes at a fixed distance, t is the thickness of the coating, and W is the width of the substrate. While conducting the experiments, we observed that the electrical conductivity in the mixed electrolyte performs best rather than the citric acid electrolyte and tartaric acid due to more inter-ionic interactions taking place between the compounds, and there is also an improvement in the dissociation of the electrolyte.

RESULTS AND DISCUSSION

Influence of machining voltage on overcut and MRR

Figure 2 shows the effect of machining voltage on overcut and MRR with various electrolytes such as citric acid, tartaric acid, and mixed electrolyte. As per the graph, an increase in the machining voltage shows the increasing trend for overcutting and MRR for all electrolytes. The tartaric acid electrolyte produces a 34 µm overcut for 7 V, 85 %, and 20 g/l, and this value is the least overcut among all electrolytes. At the same time, the least material removal was obtained for the same parameter combination. Furthermore, due to the lower conductivity of the tartaric acid electrolyte, the insulation of tool coating withstands for a longer period in the tartaric acid electrolyte, reducing the stray cut in the machining zone and producing 77.9% less overcut than in the mixed electrolyte [26]. It is apparent from Figure 3(a) that the SEM image of the micro-hole shows a smooth machining surface. For the same parameter combination, the citric acid electrolyte produces a 49 µm overcut, 44.1% less than the mixed electrolyte. In the citric acid electrolyte, the cathode releases a moderate amount of gas bubbles, which paves the way for a homogeneous supply of current density in the machining zone. This uniform current distribution of the citric acid electrolyte leads to the second lesser overcut among the electrolytes [27]. Moreover, tartaric acid and citric acid produce a 47 µm (76% improvement) and an 89 µm (24.5% improvement) overcut, respectively, for the parameter level of 8 V, 85%, and 20 g/l. It is apparent from Figure 3(b) that the SEM image shows

Table 1. Experimental results of weak electrolytes

Ex. no	Machining voltage (V)	Duty cycle (%)	Electrolyte concentration (g/l)	Machining time (s)		
				Mixed electrolyte	Citric acid electrolyte	Tartaric acid electrolyte
1	7	85	20	1279.00	1715.56	2435.46
2	8	85	20	1009.01	1242.16	1658.93
3	9	85	20	907.49	992.00	1291.99
4	10	85	20	779.62	825.68	1212.12
5	11	85	20	629.52	795.67	975.04
6	11	25	20	1179.00	1578.00	2525.25
7	11	40	20	1092.53	1288.00	1678.70
8	11	55	20	1002.00	1172.00	1321.35
9	11	70	20	730.46	1023.00	1212.12
10	11	85	20	629.52	795.67	975.04
11	11	85	12	1554.00	1652.00	2304.15
12	11	85	14	1110.77	1379.99	1543.21
13	11	85	16	924.64	1273.03	1370.61
14	11	85	18	813.42	1106.00	1163.33
15	11	85	20	629.52	795.67	975.04

Table 2. Design of experiments for mixed electrolyte

Electrolyte concentration (g/l)	Mixed electrolyte (g/l)
12	6 g/l Tartaric + 6 g/l citric
14	7 g/l Tartaric + 7 g/l citric
16	8 g/l Tartaric + 8 g/l citric
18	9 g/l Tartaric + 9 g/l citric
20	10 g/l Tartaric + 10 g/l citric

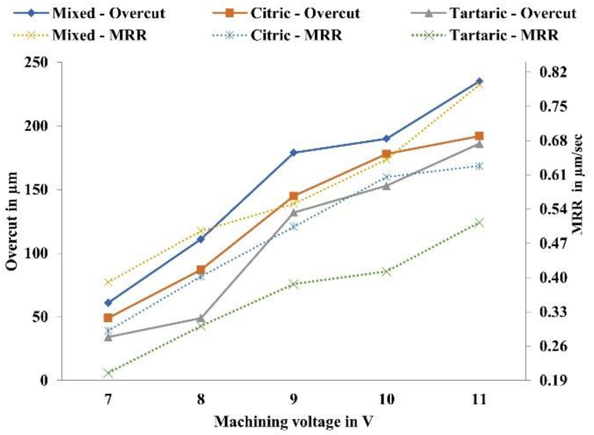


Figure 2. Influence of machining voltage on Overcut and MRR.

the less defected micro-hole on the machined surface. The mixed electrolyte produces the highest overcut, and, as is evident from Figure 3(c), the SEM image of the micro-hole shows over-etched surfaces.

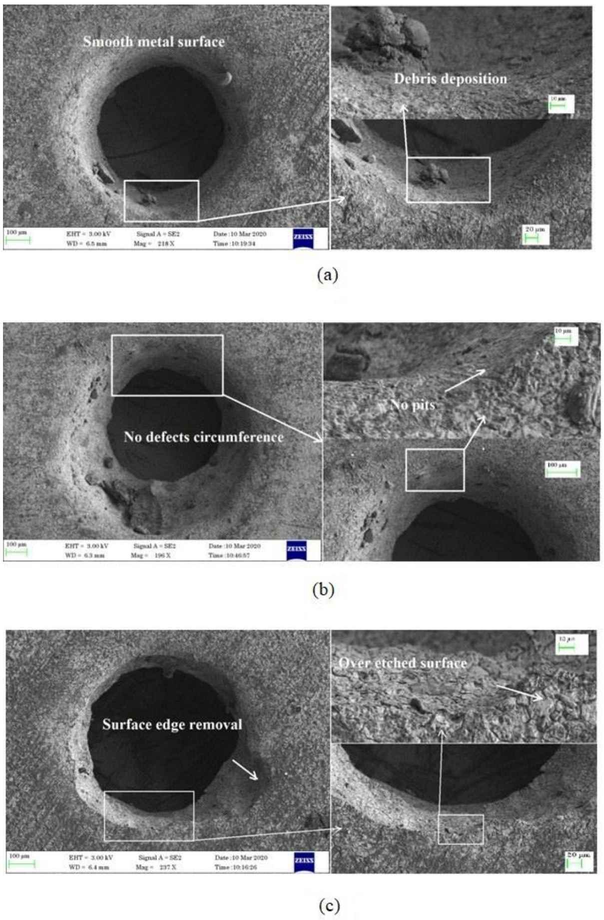


Figure 3. SEM image of the machined micro-hole at 7 V, 85 % and 20 g/l(a) tartaric acid (b) citric acid (c) mixed electrolyte.

The influence of machining voltage on MRR through various electrolytes is presented in the graph. The mixed electrolyte produces the highest MRR of all the electrolytes. In the case of a mixed electrolyte, citric acid and tartaric acid are mixed equally by weight, which accelerates the movement of ions in the electrolyte. It shows a 90.4% higher MRR than the plain citric and tartaric acid electrolytes at the parameter levels of 7 V, 85.0%, and 20 g/l. The graph indicates that the machining voltage from 7 V to 9 V shows the linear increment in MRR. While machining, the higher displacement of ions occurs in the machining zone with the help of hydronium ions. The reaction of citric and tartaric acids liberates hydrogen bubbles, which react with oxygen molecules to form hydronium ions [28]. In a mixed electrolyte, the combination of both acids doubles the formation of hydronium ions due to the citrate and d-tartrate ions [29]. Also, hydronium ions continuously migrate from one atom to another, which causes higher conductivity. The higher conductivity of the electrolyte produces the higher MRR with the mixed electrolyte. Moreover, the MRR is 64.4% and 42.2% for the mixed electrolyte, compared to the plain electrolyte at 8 V and 9 V, respectively. Also, at 11 V, it produces a 54.9% higher MRR than the tartaric acid electrolyte. The citric acid electrolyte shows the second-highest MRR compared to the tartaric acid electrolyte. Commonly, hydronium formation in citric acid is slightly higher than in tartaric acid, which causes higher conductivity when increasing the machining voltage. Citric acid produces a 41.9% higher MRR than tartaric acid electrolyte for parameter solutions of 7 V, 85%, and 20 g/l, respectively; similarly, MRR was found to be 33.5%, 30.2%, 46.8%, and 22.5% higher at machining voltages of 8 V, 9 V, 10 V, and 11 V, respectively.

Influence of duty cycle on overcut and MRR

Figure 4 depicts the effects of the duty cycle on overcut for the different electrolytes used in this experiment. It presents that tartaric acid electrolyte produces 46 µm overcut for the parameter solution of 25%, 11 V, and 20 g/l than the mixed electrolyte of 107 µm overcut for same parameter level combination and provides the enhancement of 132.9%. The production of hydrogen bubbles in the tartaric acid electrolyte at the machining zone contributes to less overcut [30]. Compared with other electrolytes, fewer hydrogen bubbles are formed in tartaric acid. This evolution of bubbles produces less distribution and provides more stable machining [31,32]. Therefore, lower overcut and good circumference were obtained in the tartaric acid electrolyte, as evident from Figure 5 (a).

At 40%, 11 V, and 20 g/l, the tartaric acid and citric acid electrolytes produce 74 µm and 98 µm overcuts, respectively. These overcut values are 94.6% and 32.40% less than the mixed electrolyte overcut of 144 µm. Also, the duty cycle of 55%, 70%, and 85% improves overcut, such as 46.9%, 56.9%, and 18.3%, respectively, with tartaric acid electrolyte than with mixed electrolyte. According to the graph, citric acid electrolyte produces less overcut than the mixed electrolyte. The citric acid electrolyte produces a 77 µm overcut for the parameter level at 25%, 11 V, and 20 g/l, and for the same parameter combination, the mixed electrolyte shows an improvement of 67.4%. Moreover, the duty cycle of 55%, 70%, and 85% improves overcut by 32.1%, 31.2%, and 25.4% with citric acid electrolyte, respectively, than the mixed electrolyte. It is evident from Figure 5 (b) that the micro-hole with an almost circular circumference and slight microcracks were found on the machining surface, and Figure 5 (c) shows the SEM image of the micro-hole with a wavier circumference that was found for the mixed electrolyte.

According to the graph, mixed electrolyte produces a higher MRR than tartaric acid electrolyte, and increasing the duty cycle increases the MRR. In the mixed electrolyte, heat generation at the machining zone is induced due to the double hydrated anions such as tartrate and citrate. Generally, a synergistic effect was developed due to the heat propagation in the electrolyte. The heating of the electrolyte increases the electrolyte density, and this lower density electrolyte conducts electricity faster than the normal electrolyte [33]. This factor is comparatively smaller in the other electrolytes. Hence, the mixed electrolyte produces a 114.2% higher MRR than the tartaric acid electrolyte for the parameter levels of 25%, 11 V, and 20 g/l. As for the citric acid electrolyte, MRR was 60% higher than tartaric acid electrolyte for the same parameter combination. It is a common fact that citrate anions are stronger than tartrate anions. Therefore, stronger acid accelerates the ion movement faster than less strong acid, which results in a higher MRR with citric acid electrolyte. Furthermore, at 55%, 70%, and 85% duty cycles, they produce a 31.9%, 65.9%, and 66.2% higher MRR with the mixed electrolyte than tartaric acid. For the same duty cycle values, citric acid produces a 12.7%, 18.4%, and 2.38% improvement in MRR than the tartaric acid electrolyte.

Influences of electrolyte concentration on overcut and MRR

Figure 6 shows the electrolyte concentration and its influences on overcut and MRR. The tartaric acid electrolyte produces a lower overcut than the mixed electrolyte. It is evident from figure 10 that the overcut for the tartaric acid electrolyte of 53 µm is attained, which is less than the mixed electrolyte for the parameter solution of 12 g/l, 11 V, and 85%. This value is around a 179% improvement and the least overcut

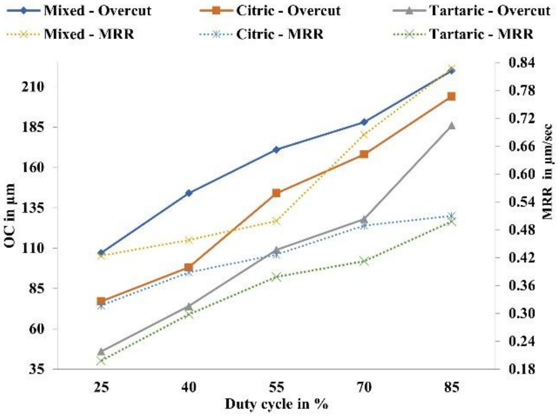
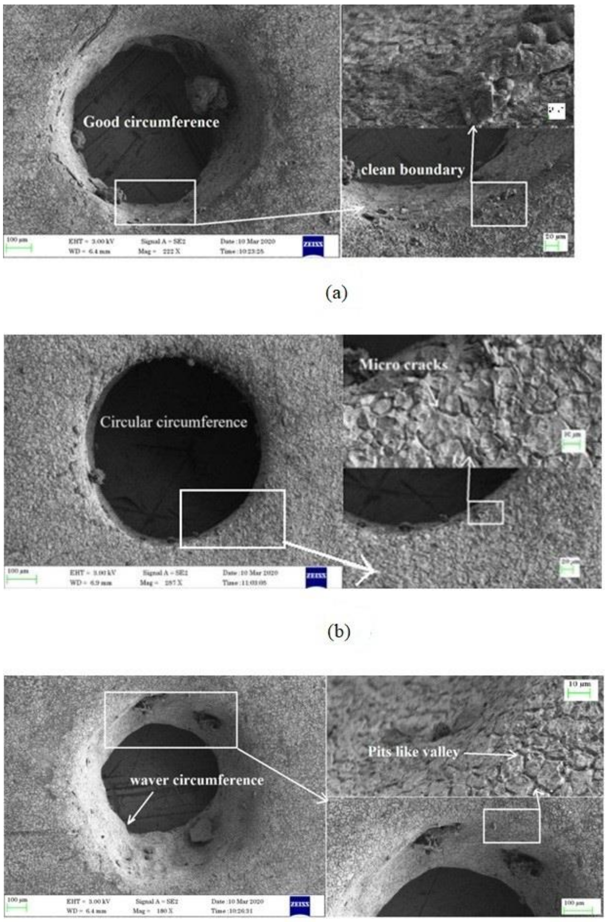


Figure 4. Influence of duty cycle on Overcut and MRR.



(a)

(b)

(c)

Figure 5. SEM image of the machined micro-hole at 25%, 11 V, and 20 g/l (a) tartaric acid (b) citric acid (c) mixed electrolyte.

value among the experiments. Also, the overcut is 106.2% lower at 14 g/l and 61.3% lower at 16 g/l electrolyte concentration with the same electrolyte. The causes of electrochemical reactions such as electrolyte softening, heat production, and debris stuck in the machining zone are comparatively very small in the tartaric acid electrolyte.

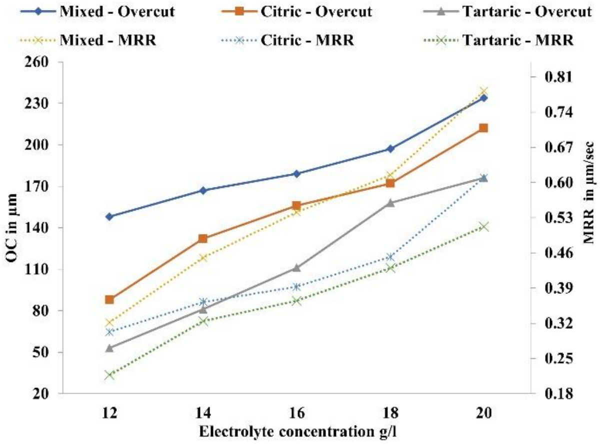
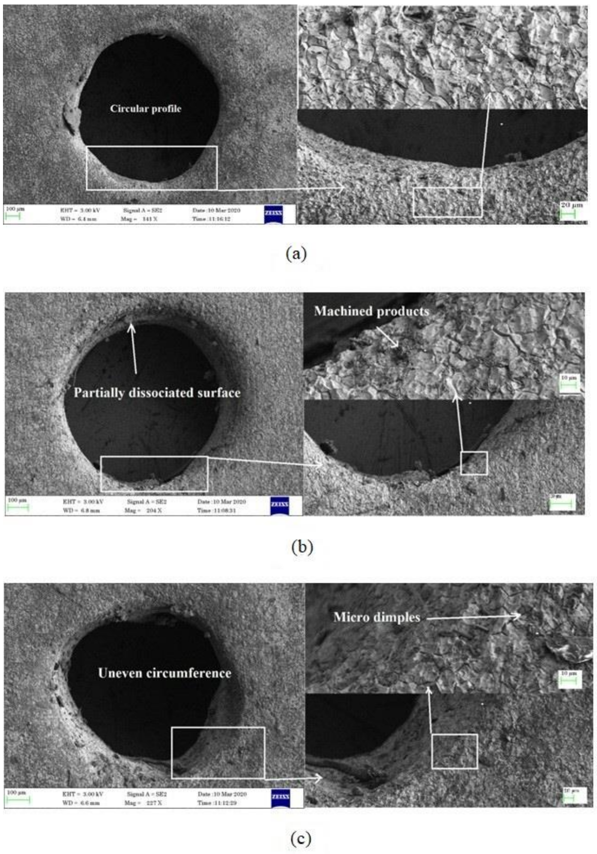


Figure 6. Influence of electrolyte concentration on overcut and MRR.

Therefore, less overcut is obtained for the tartaric acid electrolyte. Figure 7 (a) shows the SEM image of a machined micro-hole for tartaric acid with a neat circular profile. The second lesser overcut is observed for the citric acid electrolyte. It is apparent from the graph that the citric acid electrolyte shows an 88 µm overcut, which is 66% less compared to the mixed acid electrolyte for the parameter level at 20 g/l, 11 V, and 85%.



(a)

(b)

(c)

Figure 7. SEM image of machined micro-hole at 12 g/l, 11 V, and 85% (a) tartaric acid (b) citric acid (c) mixed electrolyte.

With the citric electrolyte, the continuous production of gas bubbles eliminates the machined products from the inter-electrode gap by its pulling force. This factor prevents the stray current effect and maintains a debris-free machining zone. Hence, the citric acid electrolyte produces the least overcut compared to the mixed acid electrolyte. Figure 7(b) presents its micro-hole SEM image with a partially dissociated surface. Again, a mixed electrolyte produces the highest overcut of all electrolytes. It is evident in SEM images, Figure 7(c), which presents the uneven circumference of the micro-hole.

It is apparent from the graph that mixed acid electrolyte gives a higher MRR compared with tartaric acid electrolyte. In the mixed acid electrolyte, the machined products play a major role in the higher MRR. It is a general fact that an increase of ions in the electrolyte solution increases the mobility of electrons. The higher concentrated electrolyte obtained through the mixed electrolyte, i.e., citrate and tartrate ions, accelerates the electrons faster than the individual electrolytes.

This phenomenon increases the conductivity of the electrolyte, resulting in higher sludge formation. As a result, for the parameter level of 12 g/l, 11 V, and 85%, the mixed acid electrolyte produced a 48.3% higher MRR than the tartaric acid electrolyte. Likewise, citric acid shows the next highest, i.e., 39.3% improved MRR than tartaric acid electrolyte for the same parameter combination. Furthermore, at electrolyte concentrations of 16 g/l, 18 g/l, and 20 g/l, the mixed acid electrolyte has a 48.2%, 49.0%, and 39.0% higher MRR than the tartaric acid electrolyte, respectively. In citric acid, for the same electrolyte concentration levels, 7.6%, 5.18%, and 18.9% higher MRR are obtained than the citric acid electrolyte.

CONCLUSION

In this present work, micro-holes are fabricated on SS 316L material using different electrolytes such as tartaric acid, citric acid, and mixed electrolyte to identify the best electrolyte for the ECMM process results compared with each other. According to the performance results, tartaric acid produces a 179% less overcut at 12 g/l, 85%, and 11 V than the mixed electrolyte. At the same time, the citric acid shows a 66% less overcut than the mixed electrolyte for the same parameter solution. At 25%, 11 V, and 20 g/l, the MRR with the mixed and citric acid electrolytes is higher by 114.2% and 60.2%, respectively, than with the tartaric acid electrolyte. Therefore, the mixed electrolyte can be used for better MRR where accuracy is not a significant phenomenon. Compared to other electrolytes, tartaric acid is suitable for machining with smaller overcut, and citric acid produces intermediate results in all aspects. Hence, the citric acid electrolyte can be proposed for better MRR and overcut. So, further experiments can be conducted with an eco-friendly citric acid electrolyte to improve the machining performance.

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NAUČNI RAD

UTICAJ RAZLIČITIH ELEKTROLITA NA ELEKTROHEMIJSKU MIKRO MAŠINSKU OBRADU SS 316L

Upotreba nerđajućeg čelika 316L (SS 316L) u medicinskom, pomorskom, vazduhoplovnom, biomedicinskom i automobilskom sektoru brzo raste. Elektrohemijska mikro-mašinska obrada (ECMM) je prikladna za obradu SS 316L zbog njegove površine za obradu bez ivica, bez zaostalog naprezanja i visoke preciznosti. Međutim, postoje neka ograničenja u korišćenju jakih elektrolita, kao što su HCl, H_2SO_4*, KOH,* $NaNO_3$ *i NaCl, koji se navodno suočavaju sa poteškoćama u odlaganju u okolinu i problemima rukovanja. Stoga se ovaj rad bavi prevazilaženjem nedostataka koji se sreću u ECMM procesu kada se za obradu SS 316L koriste jaki elektroliti. Zbog toga se različiti organski elektroliti kao što su vinska kiselina (*$C_4H_6O_6$*), limunska kiselina (*$C_6H_8O_7$*) i kombinacija vinske i limunske kiseline (mešoviti elektrolit) smatraju se najboljim elektrolitima. Parametri procesa kao što su napon obrade, radni ciklus i koncentracija elektrolita uključeni su u određivanje performansi obrade. Performanse ECMM-a se procenjuju korišćenjem brzine uklanjanja materijala (MRR) i prekoračenja. Presecanje (overcut) uz vinsku kiselinu je 179% manje nego u slučaju mešanog elektrolita za kombinaciju uslova obrade 12 g/l, 11 V i 85%. S druge strane, mešani elektrolit pokazuje 114,2% veći MRR od elektrolita vinske kiseline za parametarske rastvore od 25%, 11 V i 20 g/l. Štaviše, limunska kiselina pokazuje drugi najmanji presek i veći MRR u svim aspektima performansi mašinske obrade. Studije emisionog skenirajućeg elektronskog mikroskopa (FESEM) se sprovode da bi se ostvario efekat elektrolita na površinu obrade.*

Ključne reči: mikro-mašinska obrada, slabi elektroliti, elektrohemija, SS 316L, MRR, presek.