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STUDY ON EFFECT OF GRAPHITE ELECTRODE ON ACCURACY OF HOLE USING ELECTROCHEMICAL MACHINING

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ABSTRACT. Graphite electrodes are widely employed in electrochemical processes due to their conductivity, chemical stability, and resilience to high temperatures. However, graphite electrode corrosion or pitting can occur under certain conditions, reducing the electrode's efficiency and longevity. In this research, 316L stainless steel is machined through electrochemical machining (ECM) process using 0.7 graphite electrode. The voltage, electrolyte concentration and duty cycle are varied to understand the effect of graphite electrode on overcut and surface area of micro-spalling affected zone (MSAZ). The MSAZ reduces with voltage. The micro-spalling in graphite electrode occurs due to chemical reactions. At lower voltage levels, the MSAZ decreases, and a linear reduction in MSAZ is noticed in the voltage range of 8 to 9 V. The micro-spalling develops micro wavy circumference affecting the hole circularity. Moreover, the salt deposition on the electrode develops undercut region in the hole.

KEY WORDS: Micro-spalling, Stainless steel, Overcut, Voltage, Electrolyte concentration, Duty cycle.

INTRODUCTION

Electrochemical machining (ECM) is a non-traditional machining technique that uses electrochemical dissolution to remove material from a workpiece. The tool, or cathode, is designed to match the negative geometry of the intended workpiece and functions as a conductor. The anode is usually a workpiece made of conductive material. ECM works on the principle of Faradays law of electrolysis [1-3]. The metal removal rate (MRR) depends on current density (J) and metal dissolution efficiency. To estimate the shape of an ECM, it's important to consider both the current distribution and the relationship between metal dissolution efficiency (Z) and current density and electrolyte flow conditions. The tool shape must match with the workpiece's material and profile. ECM tool requires superior thermal and electrical conductivity, corrosion resistance, high machinability, and stiffness to handle electrolytic pressure without vibration [4, 5]. Research on ECM cathode tool modification is pursued by many researchers, Thanigaivelan and Arunchalam [6] have used different type of cathode tips to improve the machining performance. Venugopal *et al.* [7] have used polytetrafluoroethylene coated electrode in ECM, and reported that the coated tool at 20 g/L mixed electrolyte, 8 V, 85% duty cycle, and 90-Hz frequency shows higher machining performance and accuracy.

Graphite is widely utilized as an electrode material in ECM due to its excellent electrical conductivity, corrosion resistance, and machinability. Graphite has various qualities that make it appropriate for electrochemical machining. Graphite's strong conductivity provides efficient current flow between the tool and the workpiece, which is crucial in ECM because material removal is dependent on the passage of electric current. Graphite resists chemical reactions in the electrolyte, resulting in longer electrode life and less contamination during the machining process. Graphite is generally easy to form, permitting the development of complicated tool geometries needed for precision machining in ECM. Graphite is a good electrical conductor because its atomic structure allows electrons to travel easily across atomic layers. The hexagonal, layered structure allows for features like as lubrication, intercalation, and conductivity. Graphite

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electrodes have regulated porosity, which allows them to balance strength and reactivity with electrolytes. Zhu *et al.* [8] utilized the graphite electrode in ECM for generation of micro-holes, and by carefully controlling the variables, the taper generation was significantly reduced. The optimal parameters for the generation of micro-holes are the frequency of 100 kHz, the voltage of 18 V, the feed of 1 µm/s, and electrolyte concentration of 5%. Palaniswamy *et al.* [9] have used graphite electrode along with magnet field in ECM, and the use of graphite electrode improved the machining speed by 44.5% over stainless steel electrode. Pradeep *et al.* [10] have used polymer graphite electrodes in ECM, and the maximum machining speed for graphite electrode is recorded as 0.2951 g/min, at 9 V, 29 g/L, and 60% of duty cycle ratio. The overcut phenomenon reduces as the process parameter levels decreases. Tang *et al.* [11] studied the effect of graphite mixed electrolyte in electrochemical discharge machining. Adding graphite powder to the electrolyte increased the hole's entrance diameter at depths more than 200 µm. The HAZ width rose with increasing hole depth at 37-41 V, but decreased at 43 V. A reduction in hole taper angle ranging from 0.5° to 2.3° was achieved. Zhan *et al.* [12] have performed electrochemical polishing with the help of graphite network electrode which is embedded in the polishing pad, and is biased anodically. The workpiece, copper surface is oxidized and removed efficiently with the graphite electrodes. Zeis [13] have used thin graphite electrodes in electric discharge machining with high aspect ratio. The use of thin graphite electrodes sporadically results in geometrical errors.

It is evident from the literatures that the use of graphite electrode in the ECM is sparse, and application of graphite electrode in the ECM improves the machining efficacy. In this research, a commercially available pencil tip is used as a graphite electrode, and process variables such as voltage, electrolyte concentration, and duty cycle are varied to study their effects on overcut and the micro-spalling affected zone (MSAZ).

EXPERIMENTAL

Figure 1 depicts the ECM setup used for machining the 316 stainless steel (316L SS) workpiece. The ECM setup comprises chrome coated angle plates, assembled in such a way that tool movement can be performed properly. The stepper motor is mounted on the top angle plate, which is secured to the vertical column with Allen screws. The mechanical coupling between the stepper motor and the threaded lead screw facilitates the tool up and down movement. The tool holder slides on the lead screw during the rotation of the lead screw. The copper tool holder is attached to the tool feeder with wooden fabricated block. The electrolyte supply system has chemical pump, filter, and nozzles. The stepper motor rotation was controlled by the microcontroller program, and the pulse power supply is connected with electrodes [14]. The graphite tool electrode, a commercially available pencil tip with a diameter of φ700 µm, is used as cathode, while 316 L SS with a thickness of 200 µm is used as an anode.

Figure 2 and 3 presents the EDAX for the graphite electrode and 316L SS, respectively, showing that all the entire alloying materials were present in the anticipated composition. The pulsed power supply with varying voltage and duty cycle was used in this study. The electrolyte was prepared by dissolving sodium nitrate ($NaNO_3$) salt in distilled water and stirred for proper mixing [15, 16].

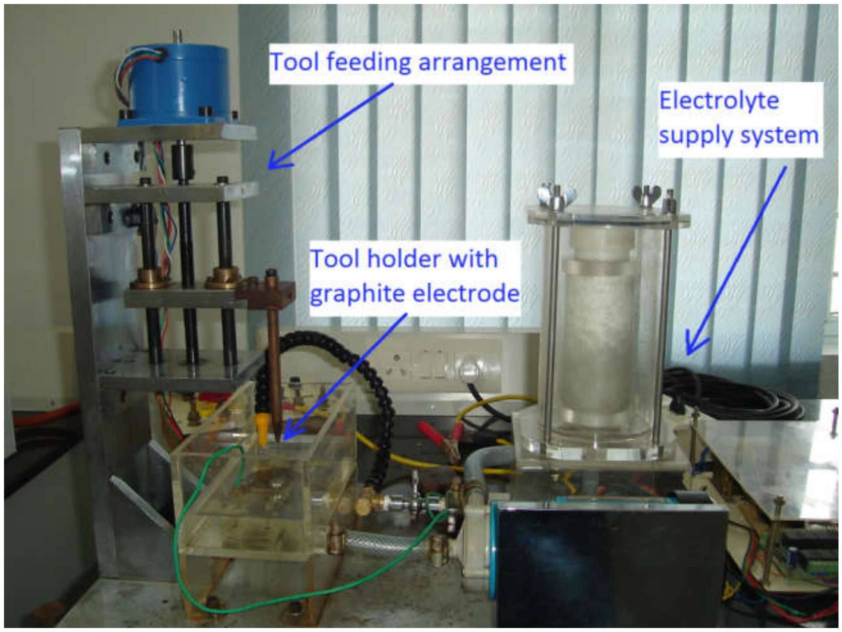

Figure 1. Experimental setup.

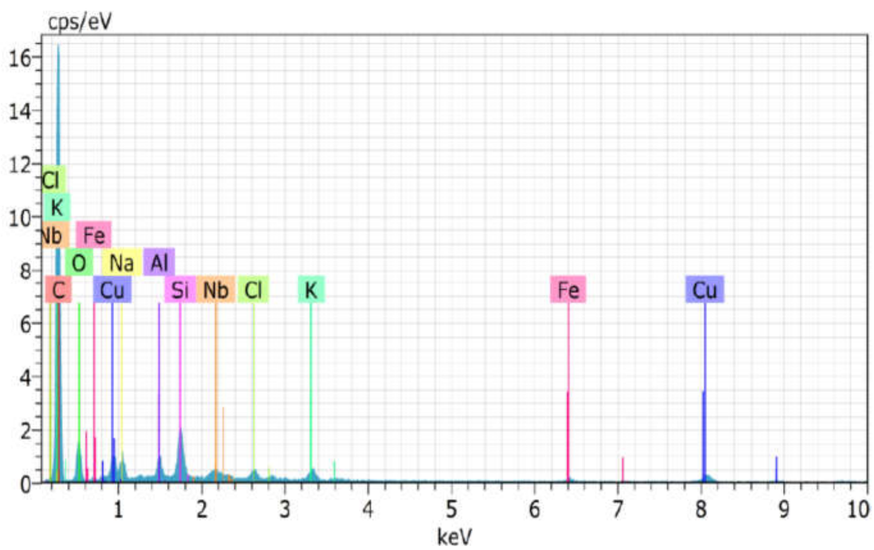

Figure 2. EDAX of Graphite electrode.

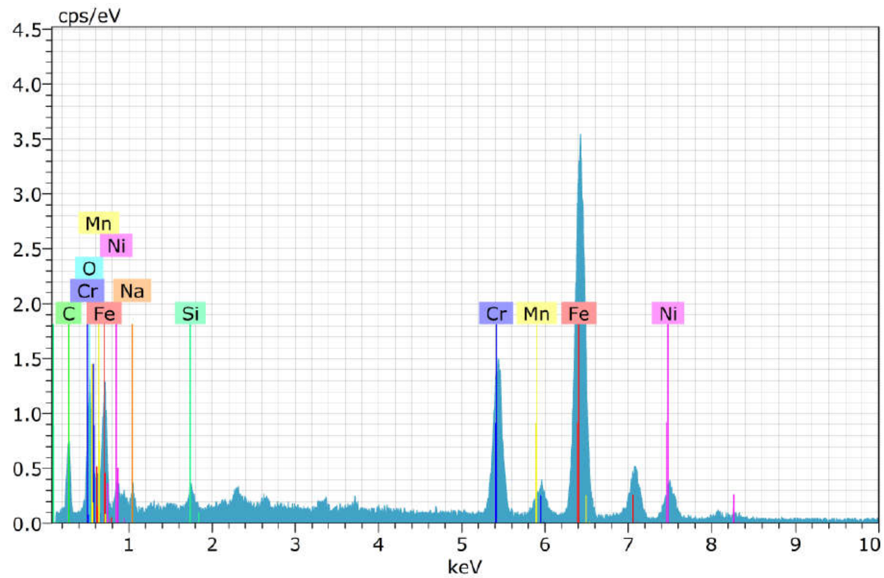

Figure 3. EDAX of 316L SS.

Table 1 presents the voltage, electrolyte concentration and duty cycle levels, respectively, along with overcut and surface area of MSAZ values [17]. The ECM hole making experiments were conducted by varying one parameter at a time keeping the other highest levels constant. The overcut is calculated based on the optical microscope image and difference between the machined hole and electrode diameter provides the overcut values [18, 19]. The surface area of MSAZ is calculated using surface area of cylinder formulae and SEM images were used to measure the height and area of the micro-spalling zone. Figure 4(a) and (b) depicts the pictorial representation of the graphite electrode with micro-spalling and overcut in the workpiece.

Table 1. Experimental settings.

S. No.	Voltage in volts	Electrolyte concentration (g/L)	Duty cycle in %	Overcut in μm	MSAZ x 10^6 μm^2
1	6	35	90	320	1.646
2	7	35	90	350	1.624
3	8	35	90	420	1.580
4	9	35	90	520	1.382
5	10	35	90	409	1.316
6	10	15	90	280	1.690
7	10	20	90	320	1.668
8	10	25	90	484	1.624
9	10	30	90	400	1.620
10	10	35	90	335	1.591
11	10	35	50	250	2.204
12	10	35	60	388	2.134
13	10	35	70	554	2.086
14	10	35	80	480	2.042
15	10	35	90	350	1.910

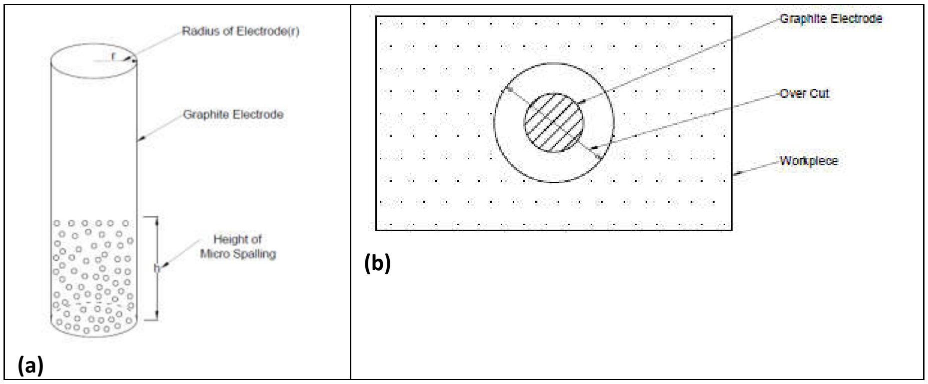

Figure 4. (a) Sketch of graphite electrode with micro-spalling and (b) overcut in the work piece.

RESULTS AND DISCUSSION

Figure 5 represents the effect of voltage on overcut and MSAZ. The overcut increases with voltage and then decrease. This is owing to the fact that the increase in voltage enhances the electrochemical reaction. The linear increase in overcut is noticed in the figure for the voltage range of 7 to 9 V. In ECM, the material removal performance is associated with the amount of electricity passed through the electrolyte. Other factors influence the anode material removal is electrode conductivity and shape, temperature of electrolyte and methods of scavenging the debris. In this research, the use of graphite electrode significantly reduced the overcut [4]. The use of graphite electrode enhances the conductivity in the electrolyte attributing for increased dissolution [20]. This phenomenon attributes for higher overcut in the hole. The decrease in overcut is observed with an increase in voltage. This is due to the fact that at higher voltages, more reaction products accumulate in the machining area, reducing the electrolyte conductivity. The reduction in electrolyte conductivity leads to a decrease machining efficacy, resulting in a reduced overcut. The MSAZ reduces with voltage, the micro spalling in graphite electrode occurs due to chemical reactions. At lower voltage levels, the MSAZ is smaller, and a linear decrease in MSAZ is noticed for the voltage range of 8 to 9 V. At lower voltages, the dissolution efficiency is low, and long duration of machining exposes the graphite electrode to chemical stress [21]. The decrease in MSAZ is witnessed due to high machining efficacy at higher voltage with short duration machining.

Figure 6 shows the effect of electrolyte concentration on overcut and MSAZ. The graphite electrode is shown in Figure 7 (a) and (b), illustrating the condition of the electrode before and after machining. The overcut is minimal at 15 g/L of electrolyte concentration. Although the electrode has enhanced conductivity, the ions associated with machinability are fewer, resulting in less overcut. While increasing the electrolyte concentration of the ions availability in the electrolyte and enhanced conductivity of electrolyte promotes faster dissolution in the machining zone. The debris resulted from this dissolution impede the machining gap required for optimum dissolution. During this time, the electrochemical dissolution reduces automatically resulting in reduction of overcut. Moreover, sodium salts are often insulators in solid form. When they deposit on a conductive substance, such as graphite, they form an insulating layer that impedes electron transport across the electrode's surface, lowering total conductivity [22]. Figure 7(c) depicts the presence of sodium salts on the graphite electrodes. The MSAZ decreases from a higher level for with varying electrolyte concentrations. Figure 7 (d) demonstrates the micro-spalling effect on the machined hole. The micro-spalling develops micro wavy circumference affecting the hole circularity. Moreover, the salt deposition on the electrode develops undercut region in the hole. Salt deposits can also change the surface shape of the graphite electrode, resulting in uneven conductivity and possibly creating hotspots where electron transport is inhibited.

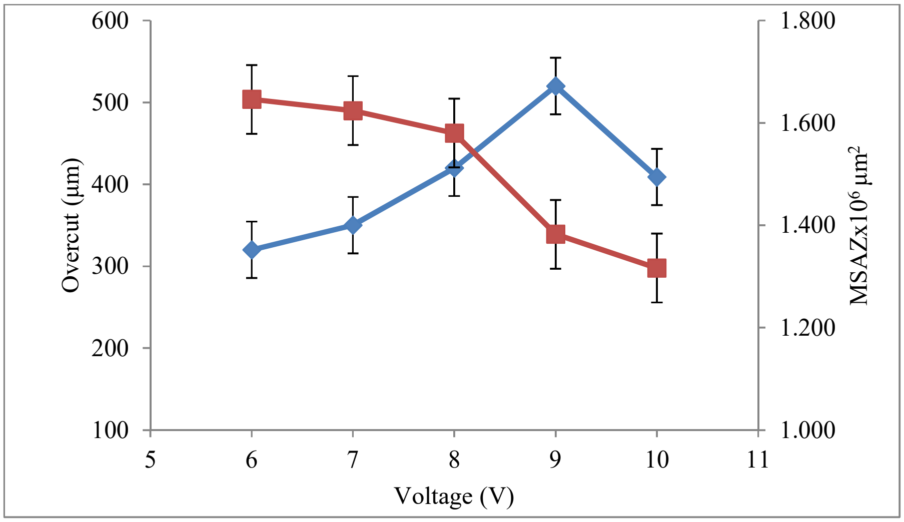

Figure 5. Voltage vs overcut, MSAZ.

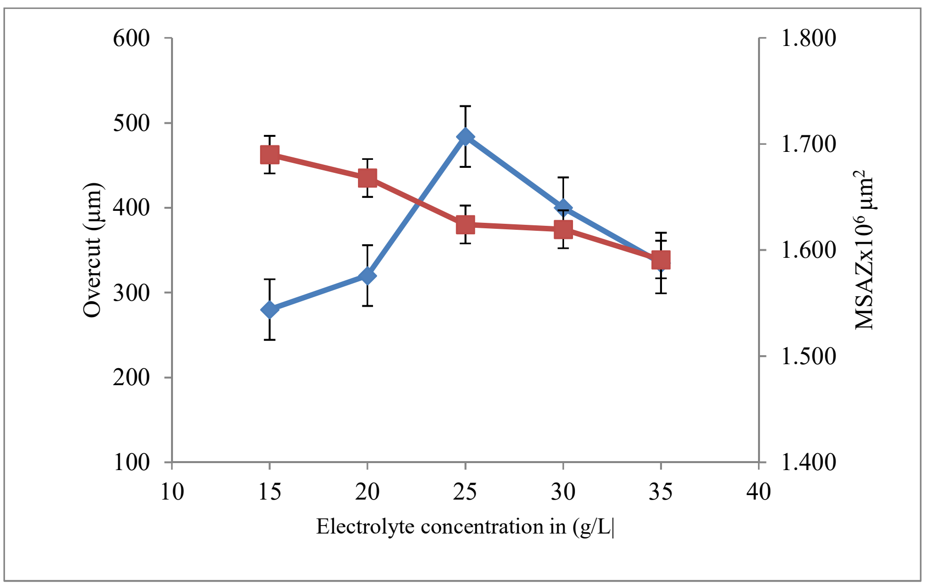

Figure 6. Electrolyte Concentration vs overcut, MSAZ.

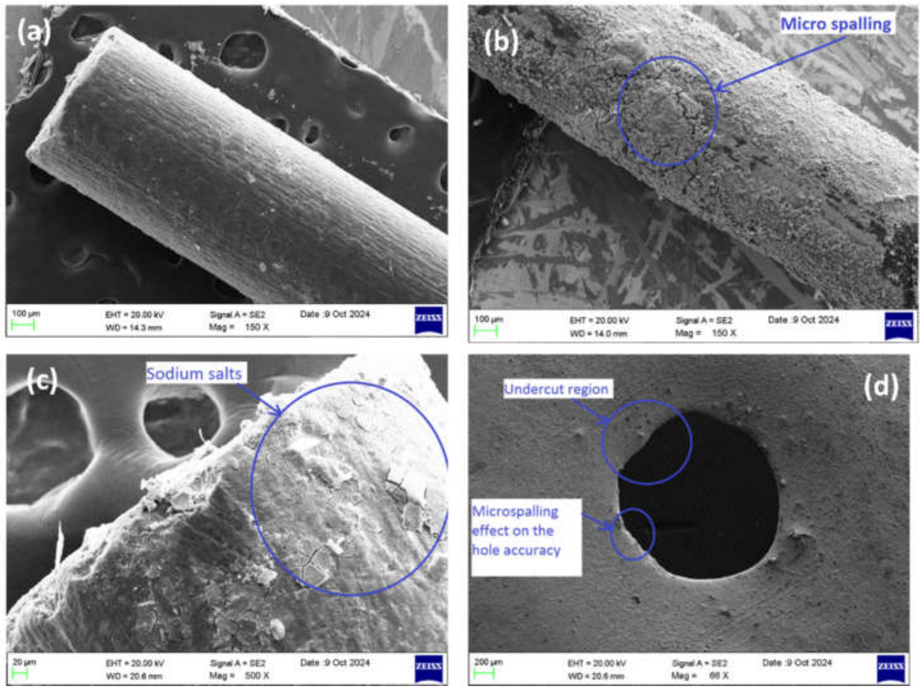

Figure 7. Electrode condition (a) before machining, (b) after machining (10 V, 35 g/L and 50% duty cycle), (c) electrode with salt deposition, and d) hole with micro-spalling effect.

Figure 8 depicts the effect of duty cycle on overcut and MSAZ. The overcut increases with duty cycle up to 70%, after which it decreases with duty cycle continues to increase. At higher duty cycles, the pulse on time is greater than the pulse off time, causing the dissolved metals in the electrolyte to reduce machining, which contributes to reduced overcut. MSAZ shows a decreasing trend as the duty cycle increases. During ECM process, the ionic contamination in electrolyte and improper current density develops pitting on the electrode. At 50% duty cycle, the pulse on and off times are equally distributed, hence the material removal and flushing of debris happens at equal time. Gases and heat can be produced during electrochemical dissolution as a result of reactions. A porous construction due to pitting allows gas bubbles to escape from the electrode surface, preventing obstruction that could impede the dissolving process [23-25]. This phenomenon attributes for lower overcut, and further increase in duty cycle shows the sharp rise in the overcut. The declining of overcut with increasing duty cycle depends on gas bubble generation on the cathode graphite electrode, non-uniform current distribution, and temporarily blockages in the electrochemical active cells.

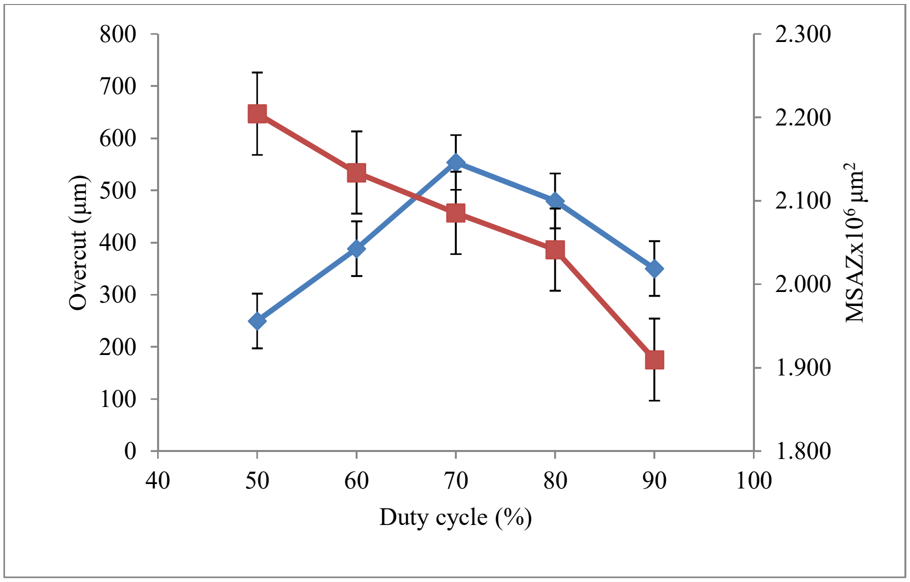

Figure 8. Duty cycle vs overcut, MSAZ.

CONCLUSIONS

The EDAX analysis for the graphite electrode and 316L SS confirmed that all the entire alloying materials were present in the expected composition. The ECM hole making experiments were conducted by varying one parameter at a time while keeping the other parameters fixed at their highest levels. The voltage, electrolyte concentration, and duty cycle were used as input variables, while overcut and surface area of MSAZ values were the ECM performance measures. The use of graphite electrode significantly reduced the overcut. The MSAZ reduces with increasing voltage, while the micro spalling in graphite electrode occurs due to chemical reactions. At lower voltage levels, the MSAZ is reduced and a linear decrease in MSAZ is noticed within the voltage range of 8 to 9 V. The overcut increases with duty cycle up to 70% and then further decreases as the duty cycle increases further. Micro-spalling develops a wavy circumference, affecting the hole circularity. Moreover, the salt deposition on the electrode develops undercut region in the hole. The reductions of overcut with increasing duty cycle rely on gas bubble generation on the graphite electrode, non-uniform current distribution, and temporarily block electrochemically active cells due to salt deposition. Proper operating conditions can extend the graphite cathode's life and effectiveness in electrochemical processes.

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