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Investigation of active surface area of tool electrode and peak current on discharge energy during ECDM process

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The Electrochemical Discharge Machining (ECDM) process is a hybrid non-conventional machining process. It is used for machinings hard and brittle materials such as borosilicate glass and ceramic materials. In the ECDM process, active surface area (dipped tool) and peak current affect the discharge energy, which further influences the quality of the micro holes. The present article is aimed to investigate the effect of active surface area and peak current on the performance characteristics during the ECDM process. Experiments were conducted to investigate the affect of active surface area and peak currenton Depth Of Penetration (DOP), the Hole Over Cut (HOC), and Material Removal Rate (MRR) based on the reaction rate during ECDM of borosilicate glass. The experimental results reveal that both the MRR and HOC increase in increasing the peak current and decreasing the active surface area. The maximum DOP and MRR were obtained at 5A peak current with 2 mm tool immersion depth and 7A peak current with 1 mm tool immersion depth, respectively. The minimum HOC was obtained at 2A peak current with a 3 mm tool immersion depth.

Keywords: Active surface area, Depth Of Penetration (DOP), Hole Over Cut (HOC), Material Removal Rate (MRR), Peak current

1 Introduction

The demand for glass material is increasing in the 3C industries due to various properties required for micro products such as mechanical, chemical, and optical[1]. To machine on glass material with the various micro features like microholes, micro channels, and micro slits, etc., is a challenging task due to the tendency to crack[2–4]. However, there are several non-conventional machining processes available to machine microholes on glass such as Micro Ultrasonic Machining (μ-USM)[5], Micro laser Beam Machining (μ-LBM)[6], Electrochemical Discharge Machining (ECDM)[3,7,8], etc. μ-LBM produces high energy during the machining process and results in surface micro-cracks on the work material. While in μ-USM, the MRR is low, and deep holes drilling is difficult. ECDM process is an encouraging method to use it for the subtractive processing of glass material with good surface quality and a high aspect ratio[9].

The ECDM process hybridizes the Electrochemical Machining (ECM), and Electric Discharge Machining (EDM) processes[10]. DC pulsed power supply is used to provide potential across the electrodes, resulting ina flow of electrons causing electrochemical reactions in the electrolytic cell called electrolysis. During electrolysis, hydrogen gas bubbles ‘evolution takes place at the cathode. Because of the coalescing of gas bubbles, these hydrogen gas bubbles form gas film around the tool electrode. The electric discharges are generated at tool tip, as the voltage is applied beyond 30 V (critical voltage). The discharge energy is utilized to drill micro holes in work material by melting and evaporation[10].

The discharge energy generated during the ECDM process depends on various factors such as peak current, applied voltage, active surface area, duty cycle, etc. The various studies have been performed with varying applied voltage, duty cycle, etc., in the ECDM process[11]. It was reported that the time required for the formation of gas films declines with applied voltage enhancement and results in increased discharge energy, which enhances the MRR[12]. It has been reported that a duty cycle is a key parameter that decides the time of discharges available for machining and surface roughness of the machined section[13]. Baoyang *et al.*(2015)[14]reported that current density is the influential parameter for gas bubbles generation and gas film formation. The current density is increased with the reduction in tool diameter and decreases with the increased depth of immersion of

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the tool. Saranya *et al.* (2017)[15] studied the effect of immersion depth and diameter of the tool electrode on the critical current and voltage. They observed that the critical current increases with the reduction in electrode resistance. The electrode resistance decreases with the increase in contact surface area of the tool electrolyte with the electrolyte. At the higher depth of tool immersion, gas film formation requires higher applied voltage across the electrodes. Subsequently, there is a requirement for higher critical voltage to break the gas film. Kolhekar *et al.* (2018)[16] proposed a methodology using discharge current of gas film characterization. The optimum combination of electrolyte concentration, electrolyte level, interelectrode gap, and machining time was suggested to achieve maximum gas film stability and minimum gas film thickness to get less overcut and taperness in the machined hole.

In the ECDM process, gas film behavior and its characterization are the decisive parameters to control the precision and repeatability of machining[17]. Active surface area and peak current play an inevitable role in the gas film formation rise time[18]. Rise time is the decisive parameter for the amount of discharge energy available during the machining. It affects the performance of the quality characteristics of the machined hole. So that there is a need to further investigate the effect of active surface area and peak current on the ECDM process. This research aims to investigate the performance of the ECD Mprocess at various input parameters (peak current and active surface area). The various experiments were performed at different values of peak current and active surface area. During ECDM process, drilled micro-hole output responses are studied. The DOP, MRR, and HOC were measured as responses characteristics.

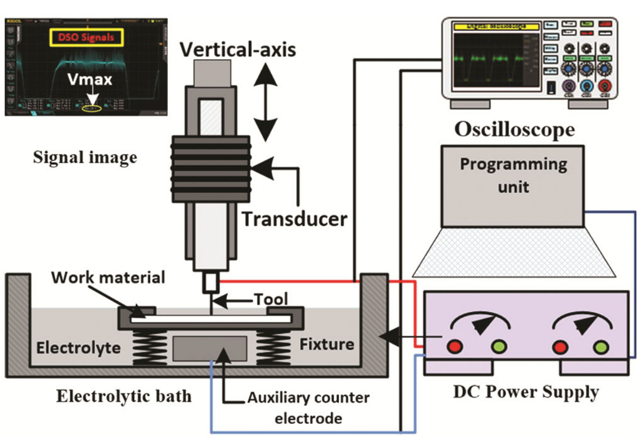

Fig. 1 — Schematic view of ECDM facility.

2 Materials and methods

The ECDM facility was used to machine borosilicate glass during the present investigation. It comprises the electrolytic cell, power supply, and work material. Figure 1 shows the schematic diagram of the ECDM facility. Tool and counter electrode were used as cathode and anode, respectively. Stainless steel (diameter: 660 µm) was selected as a tool electrode. The material for the auxiliary counter electrode was selected as graphite. The cathode was immersed in the electrolyte, and immersion depth was changed by changing the level of electrolyte in the electrolytic cell.

The one-Factor-At-a-Time method has been used in the present investigation[19–20].The process parameters used for the experiment in the present study have been listed in Table 1. An aqueous NaOH was the electrolyte used for the experiment. The borosilicate glass of thickness 1300 µm was selected as work material, and it was completely submerged in the electrolyte. ADSO (Model: DS2102, Make: RIGOL) was used to capture the voltage signals during the machining.

The DOP(µm), HOC (µm), and MRR(mg/min.) were taken as output responses. Dial gauge (Make: Mitutoyo, Model: 2109S-10P) was used to measure the DOP. HOC was calculated using Eq. 1.

$$\text{HOC}\ (\mu\text{m}) = (D_e - D_t) \quad \dots (1)$$

where the tool electrode diameter is D_t and hole entrance diameter is D_e.

The MRR was calculated by using Eq. 2.

$$\text{MRR}\ (\text{mg/min.}) = \frac{(W_i - W_f)}{T_m} \quad \dots (2)$$

where, T_m represents the machining time, initial weight is represented by $W_{i,}$ i.e., before machining, and the final weight is represented by $W_{f,}$ i.e., after machining. The machining time taken during experiments was 2 min. The work material weight was measured by the digital weighing machine

Table 1 — Process conditions for the investigations

Parameters	Values
Peak current	2 A; 3 A; 4 A; 5 A; 6 A; 7 A
Tool immersion depth	1 mm; 2 mm; 3 mm
Machining time	120 s
Electrolyte concentration	20 (% wt. /vol.)
Applied voltage	54 V
Pulse on time	3(ms)

(Shimadzu, AUW220D, Least count: 0.01 mg). The experimentation is repeated three times. The average value from all measurements was considered as output response during the experiments.

3 Results and Discussion

3.1 Effect of active surface area and peak current on output responses

Electrolysis is the primary process of starting the ECDM process. During electrolysis, the hydrogen gas bubbles evolve at the tool. These gas bubbles' generation rateis dependent on the reaction rate at the tool electrode. The reaction rate at the tool electrode can be expressed, as shown in Eq. 3[1].

$$V_{\text{reaction rate}} = \frac{I}{n*F*A} \quad \ldots (3)$$

$V_{reaction\,rate}$ is the reaction rate at the tool electrode, I is the electric current, the total number of electrons is represented by n, A is active surface area of tool electrode and faraday constant if F. It is observed from Eq. 3 that the reaction rate is inversely proportional to the acting surface area.

The acting surface area increases with more tool immersion in the electrolyte, and it reduces the reaction speed. Consequently, the gas film formation time also increases (Fig. 2). Hence, the number of electric discharges decreases, decreasing the discharge energy produced in the machining zone. But with the rise in current, the reaction rate increases, increasing the thermal energy in the machining zone. The rise time for the gas film formation is high at low peak current and decreases with increase (Fig. 2). Hence, active surface area and current are the crucial parameters, which govern the discharge energy during the ECDM process.

In the present article, crucial parameters' effect on output characteristics during ECDM process is investigated. The results obtained from experiments are shown in Fig. 3. The tool immersion depth and peak current are varied from 1 mm to 3 mm and 2 A to 7 A, respectively. The other process parameters required for the experiment were selected from the pilot experimentation, as shown in Table 1. Figure 3 shows the effect of tool immersion depth and peak current on DOP, HOC, and MRR. It is observed from Fig. 3 (a) that DOP increases with the rise in peak current from 2 A to 4 A at a tool immersion depth of 1 mm.

The reaction rate enhances with rise in the peak current as per Eq. 3. The rate of generation of gas

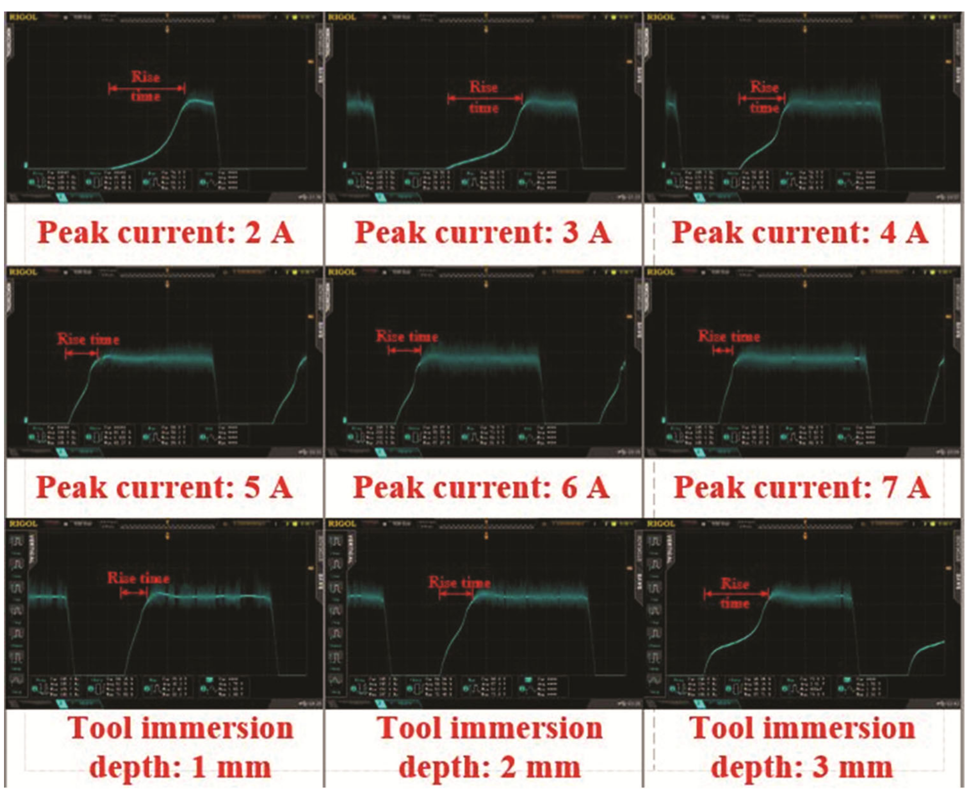

Fig. 2 — DSO images show the relation of peak current, and tool immersion depth with the rise time (Applied Voltage 54V, Electrolyte Conc. 20(% wt./Vol.), and Pulse on time 3(ms)).

bubbles increases with a peak current increase from 2 A to 4 A, which increases the gas film formation rate, increasing in discharge intensity and frequency. This leads to an increase in DOP and MRR but also increases in HOC, which is not desirable. The trend is reversed on further rise in current from 4 A to 7 A. The reason for this is the generation of a large amount of energy produced under the electrode of the tool that

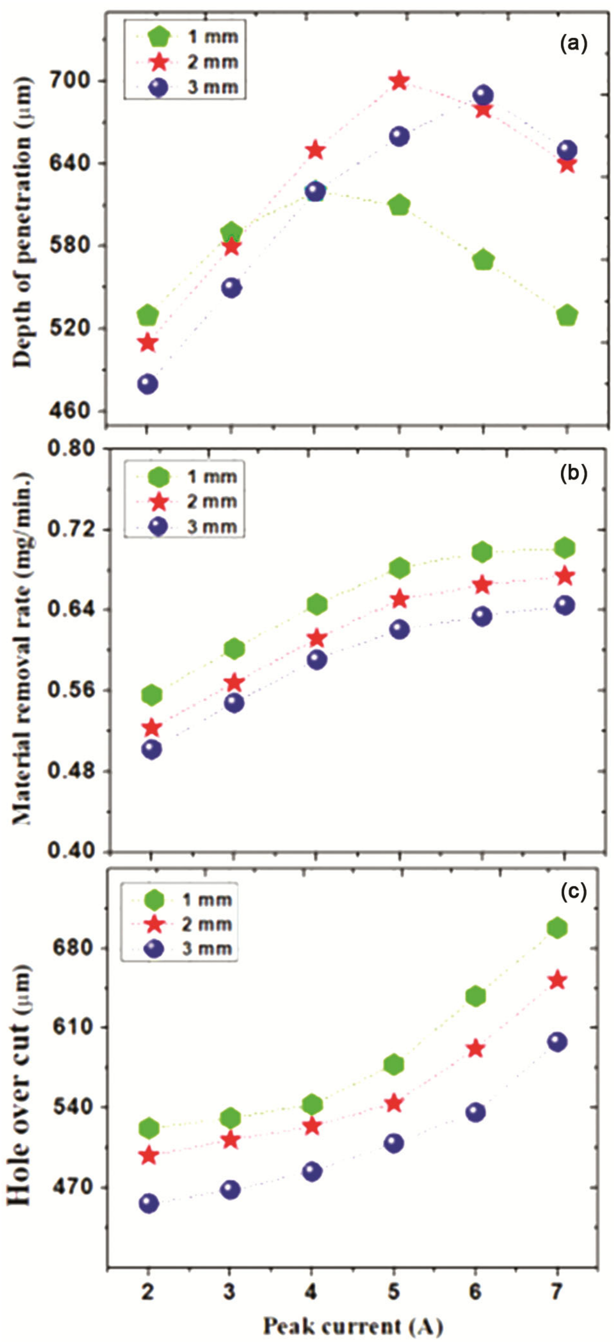

Fig. 3 — Effect of peak current on (a) DOP, (b) MRR, and (c) HOC at different tool immersion depth.

evaporates the electrolyte from there with a further rise in the peak current. Due to the electrolyte scarcity beneath the tool electrode, electrolysis process terminated, resulting in the evolution of gas bubbles at the tool electrode sidewall. At tool electrode, sidewall bubbles are accumulated, which also restricts the electrolyte flow at hole entrance. Hence, it results in a decrease in DOP. But the MRR and HOC are increasing because of side discharges, as shown in Fig. 3.

The surface area increases with more tool immersion in an electrolyte, which decreases the reaction rate as per Eq. 3, and therefore gas bubbles generation rate also decreases. The low frequency of gas film formation decreases the discharge energy available in the machining zone. Hence the DOP, MRR, and HOC decrease with an increase in immersion depth. At 2 mm tool immersion depth, the DOP and MRR increase with a rise in peak current, as depicted in Fig. 3(a and b). The DOP increases up to 5 A peak current because the energy from the discharges increases with a rise in peak current and is concentrated underneath the tool. The DOP decreases with a further rise in peak current, as observed in Fig. 3(a). The higher amount of discharge energy evaporates the electrolyte from the tooltip vicinity. Hence, there is no formation of a gas film, and therefore the DOP decreases. The MRR rises with a peak current increase from 5 A to 7 A, but the rate of increase in MRR is reduced after 5 A, as shown in Fig. 3. MRR increases because of the undesirable increase in HOC.A similar trend is observed, with the tool immersion depth from 2 mm to 3 mm increased further.

The HOC increases with a rise in peak current, as observed in Fig. 3(c). HOC gradient at 1 mm tool immersion depth is low up to 4 A peak current (HOC increase from 519 μm to 542 μm). The HOC increases significantly (542 μm to 698 μm) with a rise in peak current from 4 A to 7 A. With a rise in peak current, the discharge energy increases, but that discharge energy contributes to an unwanted increase in the HOC and reduces the form accuracy of drilled micro holes. At high peak current, large numbers of gas bubbles are generated at the tool, resulting in thicker gas film formation results in the generation of high-intensity and low-frequency discharges. High-intensity discharges produce high thermal energy and result in electrolyte evaporation. So the gas film formation takes place only on the tool electrode sidewall due to the accumulation of gas bubbles there. Breakdown of this gas film leads to side discharge generation, which increases the HOC. Figure 3 shows that when the tool immersion depth increases, the HOC decreases. The reaction rate decreases with more tool immersion in electrolyte and results in thinner gas film formation, which generates low, low-intensity, and high-frequency discharges beneath the tool electrode as well as sidewall; hence the HOC is decreased.

The results obtained from the experiments are explained with the help of the model, as present in

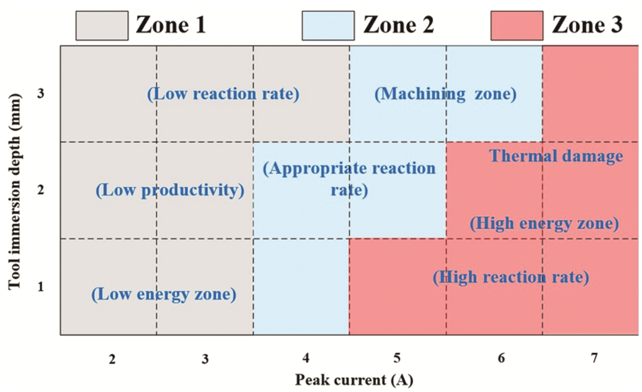

Fig. 4 — Effect of tool immersion depth and peak current on reaction rate during the ECDM process.

Fig. 4. The complete diagram is divided into three zones, such as zone 1 (Low reaction rate zone), zone 2 (Appropriate reaction rate zone), and zone 3 (High reaction rate zone). At zone 1, the reaction rate is low due to the inappropriate combination of tool immersion depth and peak current; hence the DOP and MRR are low, as depicted in Fig. 3. Zone 2 is represented as the machining zone in the ECDM process. In this zone, the DOP and MRR are maximum with acceptable HOC due to the appropriate reaction rate. The optimal gas film thickness formation takes place, which increases the ECDM process's performance.

Zone 3 is not appropriate for drilling microholes in work material during the ECDM process. In this zone, high discharge energy generates due to the high reaction rate during the electrolysis process, and that evaporates electrolytes from the machining zone. The gas film formation takes place at the sidewall of the tool electrode, and that promotes side discharges. These side discharges deteriorate the hole accuracy and enhance the surface damages, as shown in Fig. 5.

A comparative study of the ECDM process at 5 A peak current with different immersion depth is illustrated with schematic diagrams, DSO images, and microscopic images of the drilled micro-hole, as in

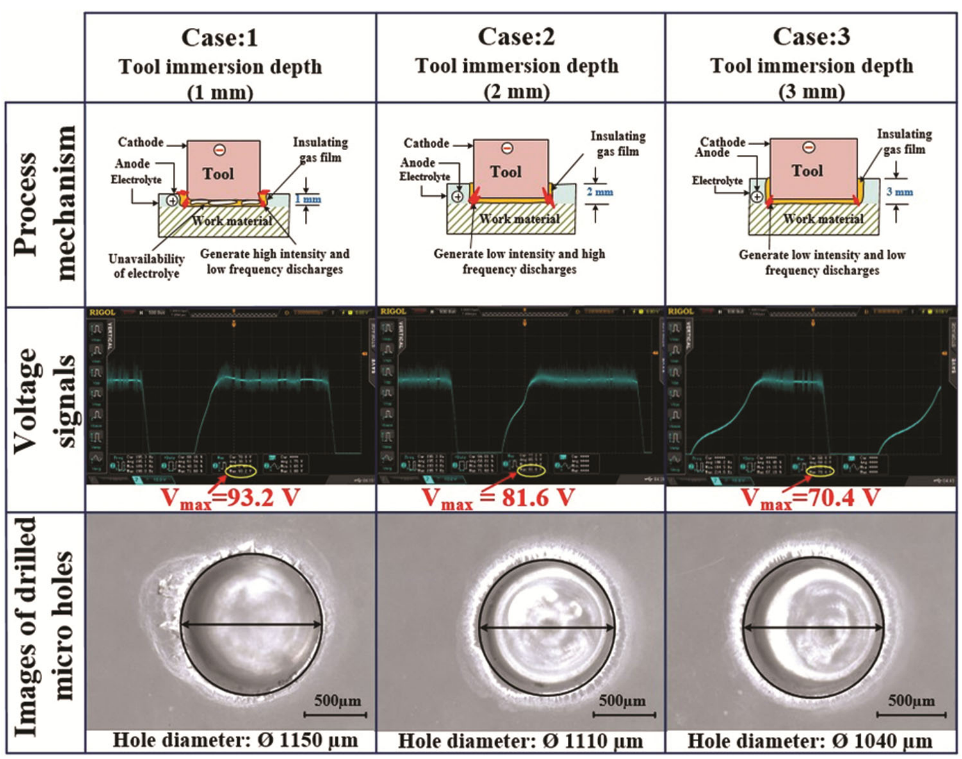

Fig. 5 — Schematic illustration of tool immersion depth effect as cases 1, 2 and 3.

Fig. 5. Three cases are considered as case 1 (tool immersion depth is 1 mm), case 2 (tool immersion depth is 2 mm), and case 3 (tool immersion depth is 3 mm). In case 1, the tool immersion depth is 1 mm, hence the reaction rate during electrolysis is high, and thick gas is formed during the ECDM process. It generates low-frequency and high-intensity discharges.

These discharges produce high temperature, which evaporates the electrolyte and formation of a thin and unstable gas film. The gas bubbles evolution from side walls form thick gas film and generate side discharges. These high-intensity discharges increase the HOC and deteriorate hole entrance quality, as shown in Fig. 5. In case 2, the rate of reaction decreases as per Eq. 3 with more tool immersion depth, i.e., 1 mm to 2 mm. The time of gas film formation increases due to the slowdown in the reaction rate, which increases the time required to start the discharges, as shown in the DSO image in Fig. 5. The gas film thickness decreases and generates low intensity and high-frequency discharges. As a result, the DOP and MRR are increased, HOC is reduced, and the microscopic images of the drilled micro hole are shown in Fig. 5. However, in case 3, the DOP,MRR, and HOC decrease with further increase in tool immersion depth to 3 mm. Excessive electrolyte level reduces the reaction rate and significant increase in the rise time. Hence, low-intensity and low-frequency discharges generate during the ECDM process, as observed in Fig. 5. The machined microhole images are shown in Fig. 5.

It can be inferred from the above discussion that the appropriate combination of active surface area and the peak current is required to achieve the process outcome with desired form accuracy. The appropriate combination of active surface area and peak current generates an optimal amount of discharge energy to achieve the desired output characteristics. In the present investigation, it is observed from Fig. 3 that the proper combinations are 4 A peak current and 1 mm tool immersion depth, 5 A peak current and 2 mm tool immersion depth, and 6 A peak current and 3 mm tool immersion depth. The quality of the drilled hole or productivity deteriorates at other parameters.

4 Conclusion

The present investigation investigated the effect of active surface area and peak current on discharge energy and their effect on ECDM process performance. ECDM process output characteristics are taken as DOP, MRR, and HOC. The main conclusions drawn from the investigations based on the experimental results are as follows:

- The reaction rate increases with peak current rise, which increases DOP and MRR.
- With more tool immersion in an electrolyte, the rise time increases due to the low reaction rate, resulting in a decrease in the discharge energy. Hence there is a decrease in DOP and MRR.
- An appropriate combination of active surface area and the peak current is required to achieve the desired output. The maximum DOP and MRR were obtained at 5A peak current with 2 mm tool immersion depth and 7A peak current with 1 mm tool immersion depth.
- The minimum HOC was obtained at a 2A peak current with a 3 mm tool immersion depth due to the small discharge energy available in the machining zone.

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