



Radial tool wear analysis and compensation strategy for microhole arrays in sequential hybrid laser beam micromachining (LBMM) and micro-EDM

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Abstract

Microhole arrays have significant applications across various industries, including aerospace, turbo machinery, industrial filtration, microfluidic devices, and biomedical engineering. Several methods exist for manufacturing microhole arrays, but the sequential hybrid laser beam micromachining (LBMM) and microelectrical discharge machining (μ EDM) process offers complementary advantages, significantly reducing production time while achieving high precision. However, due to the pre-existing tapered holes created by LBMM, tool wear during the subsequent μ EDM process primarily occurs on the sides of the electrode, leading to more significant radial wear. Reusing the same electrode results in tapered holes, while frequent electrode replacement is impractical and costly. This study investigates the tool wear characteristics in the hybrid LBMM– μ EDM process across different materials and thicknesses and proposes compensation strategies to improve machining consistency. Axial and radial tool wear lengths were characterized by machining 300- μ m microhole arrays on 600 and 200- μ m thick copper and stainless steel workpieces, with microscopic images of the electrode captured after each machining step. Analysis revealed that the hybrid LBMM– μ EDM process resulted in more prominent radial tool wear length compared to the pure μ EDM process, while the pure μ EDM process exhibited higher axial tool wear length. Radial wear was more pronounced in stainless steel than in copper, and thicker workpieces increased axial wear. To address tapering, a compensation strategy was developed by adjusting the programmed depth based on radial wear, reducing the taper angle by 7° . This approach enables the hybrid process to match the hole quality of pure μ EDM while achieving a $4\times$ faster machining rate.

Keywords LBMM · Laser · Micromachining · Micro-EDM · Microhole array · Electrical discharge machining · Hybrid · Tool wear · Compensation · Sequential

1 Introduction

Microhole arrays are essential in a wide range of industries. In aerospace applications, microhole arrays such as film cooling holes (FCHs) are critical for enhancing turbine blade cooling and thermal protection [1, 2]. Recent studies have demonstrated the feasibility of machining microhole arrays on Cf-ZrB₂-SiC, a next-generation aerospace composite material [3]. In industrial filtration, they improve heavy metal detection in water through organic membranes [4]. In

microfluidics and biomedical applications, ceramic (ZrO₂) and biocompatible microhole arrays regulate fluid flow and enable controlled drug release [5, 6]. Recent studies have explored the use of microhole arrays in microarray patches (MAPs) for targeted drug delivery and biosensing applications [7]. Moreover, microholes fabricated in PDMS polymers are particularly advantageous for these biomedical uses due to the material's low toxicity, optical transparency, and biocompatibility, enabling safe and effective interaction with biological tissues [8]. In addition, microholes are crucial in biomedical applications such as biochip fabrication, where they are replicated on glass substrates using micromolded pin arrays [9]. Microhole arrays on superhydrophobic surfaces enable self-cleaning and drag reduction [10]. In optoelectronics, silicon microhole arrays enhance optical absorption, benefiting advanced solar cells [11]. In printing, inkjet nozzles rely on microhole arrays (50- μ m diameter, 169- μ m

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pitch) for high-resolution output [12]. Graphene-based microhole arrays improve heat transfer and thermoelectric efficiency, supporting energy conversion and fuel cell performance by optimizing gas diffusion and reaction kinetics [13, 14]. The precise manufacturing of these structures ensures their reliability and effectiveness across these applications.

Various techniques are used to manufacture microhole arrays, including electrochemical machining (ECM), chemical etching, mechanical punching, microelectrical discharge machining (μ EDM), laser drilling, ultrasonic machining, and abrasive jet machining [15]. ECM offers high material removal rates (MRRs) and excellent surface quality but requires precise control and long production setup times [16]. When using non-Newtonian polyacrylamide electrolytes, ECM has created microhole arrays in stainless steel (SS304) with an average diameter of 330.11 μm and a depth-to-diameter ratio of 0.048 [17]. Chemical etching is cost-effective but can cause undercutting, temperature sensitivity, and environmental concerns. Mechanical punching is productive and cost-efficient but is limited by hole size and alignment challenges. Using punching without die technology, an array of 37 tapered microholes was successfully fabricated in aluminum alloy (Al6061) with a depth of 260 μm , demonstrating its potential for high aspect ratio holes [18]. In addition, μ EDM is precise for hard materials but is limited to conductive materials and slower speeds, as seen in stainless steel holes with diameters of 18.91 μm and an aspect ratio of 142 [19]. Laser drilling is fast and ideal for high aspect ratios but may cause heat-affected zones (HAZs) and be costly. A two-step femtosecond laser method achieved microholes in Inconel 718 with near-zero taper and high aspect ratios [20]. Ultrasonic machining is versatile for complex shapes but suffers from high tool wear and microcracks. Abrasive jet machining is cost-effective for brittle materials but can lead to tapered holes. The choice of method depends on material properties, hole specifications, and production goals.

Researchers have explored hybrid machining methods to improve micromachining performance by combining different processes to overcome individual limitations. In laser-assisted micromilling, the laser enhances material removal by heating the workpiece, increasing MRRs by up to six times [21]. A laser–electrochemical hybrid polishing process has also been studied to improve surface quality in selectively laser melted 316L stainless steel, yielding crack-free surfaces and enhanced wear resistance [22]. Another development integrates laser technology with μ EDM, where laser beam micromachining (LBMM) is used for rough machining to minimize HAZs and improve dimensional accuracy, followed by μ EDM for fine finishing. This hybrid method has reduced machining time by up to 90% and improved hole quality compared to conventional μ EDM [23, 24]. Other research observed a 50–60% decrease in machining time

with the hybrid method, without compromising hole quality, compared to standard μ EDM [25]. The hybrid approach also significantly reduces machining time, with LBMM drilling a 10-mm thick sample in just 3 s compared to 48 s with μ EDM, while producing smaller recast layers [26].

One of the remaining challenges in μ EDM is the prominence of tool wear. Extensive literature has been developed to study tool wear in μ EDM throughout the years. A 2D geometric simulation model was developed to predict electrode wear during μ EDM drilling of through-hole arrays, showing prediction errors within 5 μm for total wear and 15 μm for axial wear, improving diameter consistency by 8.02% [27]. Another study optimized pulse generator parameters to reduce electrode wear, achieving a standard deviation of 0.15 μm for a 16×16 microhole array, with smaller arrays showing similar improvements [28]. Research has also identified factors like spark discharge energy [29], machining stability [30], and piezoelectric self-adaptive μ EDM [31] as influencing wear. Compensation strategies, including predictive and real-time approaches, have been developed to enhance machining accuracy and efficiency, such as 3D grid-based models [32], electrothermal models for blind hole machining [33], robust control to maintain machining gap [34], and real-time shape-based compensation [35]. Significant progress has been made in detecting and compensating for electrode wear, improving both accuracy and efficiency.

In the LBMM– μ EDM process, the pre-existing hole created by the LBMM leads to different tool wear characteristics compared to pure μ EDM process. Due to the tapered prehole created by LBMM, tool wear during μ EDM is predominantly observed on the sides of the electrode, leading to more significant radial wear length compared to axial wear length. However, there is limited literature that investigates this distinction and its implications in detail. A recent study investigated the behavior of μ EDM drilling on preholes to improve process performance and machining accuracy [36]. Titanium alloy sheets were used with electrode diameters of 300 μm to evaluate the effects of prehole diameter, electrode type, centering accuracy, and hole depth. Results showed that preholes significantly enhance performance compared to traditional EDM drilling due to reduced debris contamination in the machining zone. Increasing the prehole size caused minimal changes in MRR. The electrode type (cylindrical or tubular) influenced only the geometrical characteristics, not process performance. Misalignment of the final hole on the prehole improved debris flow and efficiency but only when part of the prehole remained outside the final hole. Within the experimental limits, hole depth had no effect on the results. Furthermore, similar studies show that the primary factor improving drilling efficiency in the hybrid process is not the material removal by the laser but the predrilled hole's role in aiding debris and bubble exclusion during μ EDM [24]. The study confirms this claim by

demonstrating that upsetting the laser-drilled hole facilitates debris and bubble removal in deep-hole μ EDM by enlarging the exit diameter.

As far as the authors are aware, no studies have yet investigated the tool wear characteristics of μ EDM in the sequential hybrid LBMM– μ EDM process. Although μ EDM produces high-quality microholes with good dimensional accuracy, its machining speed is relatively slow. To overcome this limitation, the sequential hybrid LBMM– μ EDM approach is used, combining the fast material removal capability of LBMM with the precision of μ EDM. However, tool wear in the sequential hybrid LBMM– μ EDM process continues to be a concern, particularly for the fabrication of a microhole array. If tool wear can be effectively compensated while maintaining a high machining rate, this sequential hybrid process can achieve both speed and accuracy in microhole fabrication. Moreover, reusing the same electrode for subsequent holes causes tapering in the microholes, while frequent electrode replacement is impractical. Additionally, cumulative wear becomes significant when drilling arrays of microholes, particularly in thicker materials and varying material types.

This paper explored the μ EDM tool wear characteristics in the sequential hybrid LBMM– μ EDM process and developed compensation strategies to improve machining consistency for microhole array fabrication. The axial and radial wear length of the microelectrode was characterized by machining 300- μ m diameter microhole arrays on 600 and 200- μ m thick copper and stainless steel workpieces. Using a microscopic camera, images of the microelectrode were captured after each machining step, allowing for precise measurements of axial and radial wear length. Based on these findings, a compensation strategy was proposed to calculate the required machining depth and mitigate the impact of tapering on the quality of successive microhole arrays while maintaining fast processing speed.

2 Materials and methods

This section details the experimental setup used to investigate axial and radial wear length on the hybrid LBMM– μ EDM process, including the specific equipment and procedures employed. Additionally, the characterization techniques used to assess the performance and precision of the system are outlined, offering a comprehensive understanding of the experimental procedures and evaluation.

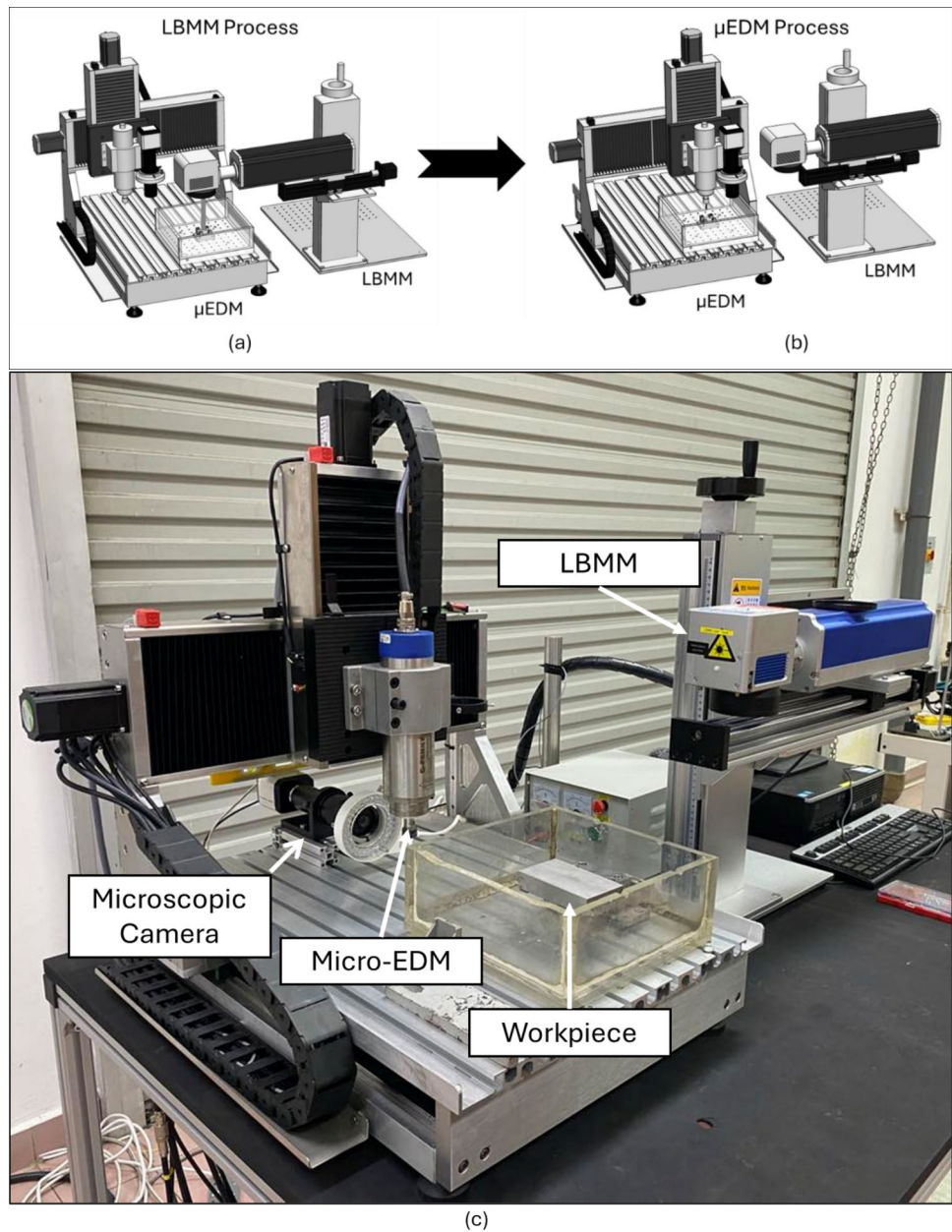
2.1 Hybrid LBMM– μ EDM setup

The integrated LBMM and μ EDM system, developed in-house [37], features the LBMM system positioned horizontally offset from the μ EDM setup. The workpiece remains within the μ EDM workspace, accessible for

both processes. The LBMM system features a 50-W fiber laser (1060-nm wavelength, 50- μ m spot size, 200-mm focal length) controlled by an X/Y galvanometer scanner with $\pm 15^\circ$ scan angle and 12- μ rad resolution. Laser power was calibrated using a Gentec Pronto-250 power meter, which measures average output power. The calibration was performed across a range of 10% to 100% laser settings. Although the laser is rated at 50 W, the actual output at 100% was approximately 38.6 W. This represents a power loss of about 22.8%, which aligns with the data provided by the supplier of this fiber laser system. This loss occurs because the laser beam passes through several optical elements such as collimators, beam expanders, mirrors, and the galvanometric scanner before exiting the system. Each optical component contributes to reflection, scattering, or absorption losses, resulting in reduced power delivered to the workpiece surface. A calibration curve was established to map the percentage settings to actual output power. For this experiment, the laser was set to 90%, corresponding to a calibrated power of 35.4 W. The laser head is height-adjustable via a rotary handle and moves horizontally on a motorized linear stage, with process parameters managed through EZCAD Lite software. The μ EDM setup, a three-axis CNC machine with 15- μ m repeatability, operates in the same workspace and includes a μ EDM spindle and microscopic camera mounted on the Z-axis plate. Custom software handles camera viewing, parameter adjustment, G-code execution, and axis monitoring. Figure 1 illustrates the machine configuration: during LBMM (Fig. 1a), the laser head positions above the workpiece; after retracting, the μ EDM system moves in for machining (Fig. 1b), with the transition taking 36 s.

A microscopic camera, mounted on the μ EDM machine, is used to establish a common coordinate system for both the camera and the μ EDM electrode [37], as depicted in Fig. 1a,b. During the calibration process, a blind reference hole is machined using μ EDM at known coordinate positions. The microscopic camera is then moved using the CNC stages to align its crosshair overlay with the center coordinates of the reference hole. The x and y deviations, representing the offset distances between the electrode and the camera crosshair, are determined using linear scale feedback. These offset distances are subsequently utilized by the μ EDM machine to transition seamlessly between the camera view and precise electrode alignment. Additionally, a second microscopic camera is positioned at the rear of the μ EDM machine, as illustrated in Fig. 1c for optical microscopic measurement (OMM), characterization, and measurement purposes. It is specifically used to measure the axial and radial wear length of the tool. The measurement accuracy, along with the associated uncertainty, is determined by the resolution and repeatability of the CNC positioning stages, specified as 1 and ± 15 μ m, respectively. Figure 1c also

Fig. 1 Illustration and configuration of the hybrid LBMM– μ EDM integrated setup. **a** LBMM process in operation. **b** μ EDM process in operation. **c** Complete experimental setup



demonstrates the hybrid LBMM– μ EDM integrated setup for the experimental work.

2.2 Experimental plan

To study the tool wear characteristics for μ EDM in the hybrid process, six sets of experiments, with different workpiece materials (copper and stainless steel) and thicknesses (200 and 600 μm), were conducted. The machining process involved the creation of an array of six LBMM pilot micro-holes, evenly spaced 1 mm apart in a 3×2 arrangement, followed by fine finishing of through-holes using μ EDM with a 300- μm diameter tungsten electrode (as available in the lab). The size of the LBMM pilot hole is critical. If the pilot hole

is too small, it increases the μ EDM machining time due to limited access and inefficient material removal. Conversely, if the pilot hole is too large, it results in excessive HAZs, recast layer, and residual spatter, which may affect the final hole quality. Therefore, a suitable LBMM pilot hole size was determined through initial trials to optimize both machining efficiency and hole quality. The selection of LBMM parameters used in this study is described in the following section. Detailed parameters for LBMM and μ EDM are tabulated in Table 1. The LBMM process used 75 loops count with a scanning speed of 10 mm/s, a 0° hatch angle, 0.01-mm line spacing, and a 50- μm focal spot size. A two-way hatch pattern was applied to enhance coverage uniformity and minimize unprocessed areas.

Table 1 LBMM and μ EDM parameters

LBMM Parameters	
Loop Count	75
Programmed Diameter (μm)	180
Scanning Speed (mm/s)	10
Laser Rated Power (W)	50
Actual Measured Laser Rated Power (W)	38.6
	35.4 (or 90%)
Applied Laser Power (W)	22 (or 50%)
	8.62 (or 10%)
Frequency (Khz)	50
Hatch Angle ($^{\circ}$)	0
Line Space (mm)	0.01
Focal Spot Size (μm)	50
Hatch Type	Two Way Hatch 
μ EDM Parameters	
Power Supply Type	Resistor- Capacitor (RC)
Resistance ($\text{K}\Omega$)	1
Electrode Material	Tungsten
Electrode Diameter (μm)	300
Workpiece Material	Copper and Stainless Steel
Workpiece Thickness (μm)	200 and 600
Gap Voltage (V)	90
Capacitance (nF)	10 (1.8 Stray Cap)
Discharge Energy (μJ)	40.5
Spindle Speed (RPM)	1200
Feedrate ($\mu\text{m/s}$)	5
Flushing Method	Atmospheric Pressure
Dielectric Fluid	Mineral based EDM oil
Polarity	Workpiece: Positive, Tool: Negative

The electrode was flattened at the bottom before each set of array hole machining to ensure a consistent electrode shape across all sets of microholes. The pregrinding was performed using the block electrical discharge grinding (EDG) method. The influence of flattening the bottom of the electrode on radial wear is not within the scope of this study. However, this step was carried out to eliminate variability in electrode shape and to minimize potential bias in wear measurements. The flatness of the electrode was visually verified using the microscopic camera, and care was taken

to ensure that no significant axial or radial wear was present before machining was performed.

Surface detection was performed for each hole, setting the Z-position to zero and retracting the electrode 100 μm above the surface. To ensure complete cuts through the 200 and 600- μm thickness of workpieces, a programmed depth of 600 and 1000 μm was used, respectively. Using a microscopic camera, images of the microelectrode were captured after each machining hole, allowing for precise measurements of axial and radial wear length. Furthermore,

the machined samples were cleaned with isopropyl alcohol (IPA), followed by cleaning in an ultrasonic bath [38]. A scanning electron microscope (JSM-IT100 from JEOL Ltd.) was used to characterize the machined hole. Third-party software named ImageJ [39] was used for characterization and subsequent measurement purposes.

The selection of workpiece and electrode materials in LBMM- μ EDM is important for achieving high precision and efficiency. In μ EDM, the electrode material affects the accuracy and shape of the machined microfeatures. Tungsten was chosen as the electrode material due to its high thermal wear resistance and low tool wear rate [40]. In this study, a cylindrical tungsten electrode with a 300- μ m diameter was used to ensure consistent machining performance.

For the workpiece, copper and stainless steel (SS) were selected due to their suitability for both EDM and laser machining. Copper was chosen for its high electrical and thermal conductivity, which ensures efficient material removal during μ EDM and good laser energy absorption in LBMM. Stainless steel was selected for its high strength, corrosion resistance, and dimensional stability, making it an excellent choice for precision microfabrication. Both materials are commonly used in biomedical devices, aerospace components, industrial filtration, and inkjet nozzles, where microhole arrays require high accuracy, durability, and performance.

2.3 Characterization

This section focuses on the characterization of key performance metrics, including axial and radial wear length measurement methods and hole quality assessment.

2.3.1 Axial and radial wear length measurement

The axial and radial tool wear length (ATWL and RTWL, respectively) was measured using images captured by a microscopic camera after each successive machining process. Axial wear was determined by measuring the distance from the tool's zero reference point, set by the machining coordinate G57, to the initial condition of the electrode tip. Radial wear length, on the other hand, was measured as the distance from the electrode tip to its original, unaltered diameter. Figure 2 illustrates the measurement method for radial and axial wear length on the electrode.

2.3.2 Machining performances

Machining performance is assessed by evaluating the machining time and the quality of machined microholes. In the LBMM process, machining time is recorded in its own graphical user interface (GUI), while for the μ EDM process, it is defined as the time required for the electrode to travel

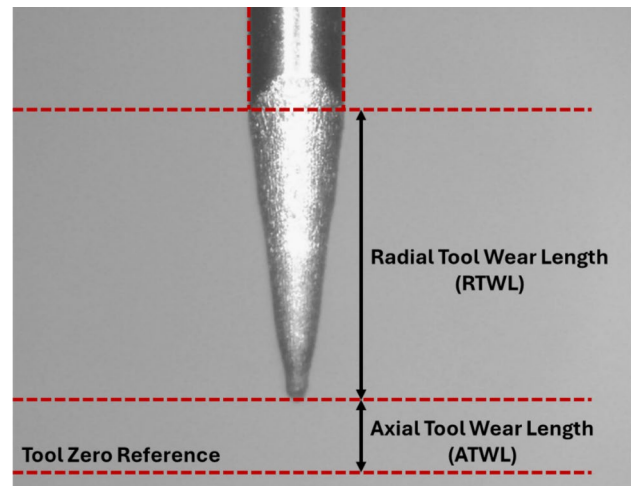


Fig. 2 Measurement of axial and radial wear length

from the workpiece surface to the programmed machining depth. This duration is calculated using Z-axis positional data, which is recorded every 100 ms. The Z-axis positional data also offers insights into the machining progression, enabling the detection of deviations or irregularities during the process. For hybrid machining, the total machining time is the sum of the LBMM and μ EDM durations. Figure 3a,b depicts the measurement method for the entry and exit diameters from the SEM images of the copper workpiece, which is essential for taper angle measurement. The same method was applied to the stainless steel workpiece.

Tool wear causes a taperness in the holes during the μ EDM process. The entry hole will have a different diameter than the exit hole. With reference Fig. 3c, the following formula is used to determine the taper angle, θ :

$$\theta = \tan^{-1} \left(\frac{d - b}{2 \cdot h} \right) \quad (1)$$

where d is the entry hole diameter, b is the exit hole diameter, and h is the thickness of the workpiece.

2.4 Study on the selection of LBMM process parameters

The performance of the hybrid LBMM- μ EDM process is strongly influenced by key machining parameters from LBMM, including laser power (P), scanning speed (SS), loop count (L), and programmed diameter (PD). For this study, predrilled LBMM holes were used as the initial step to facilitate the subsequent μ EDM process. The selection of parameters was guided by their effects on LBMM entry and exit diameters, recast layer area, LBMM processing time, and the final hybrid machining time. Laser power dictates the energy delivered per pulse, scanning speed controls the exposure time on the workpiece, and loop count determines

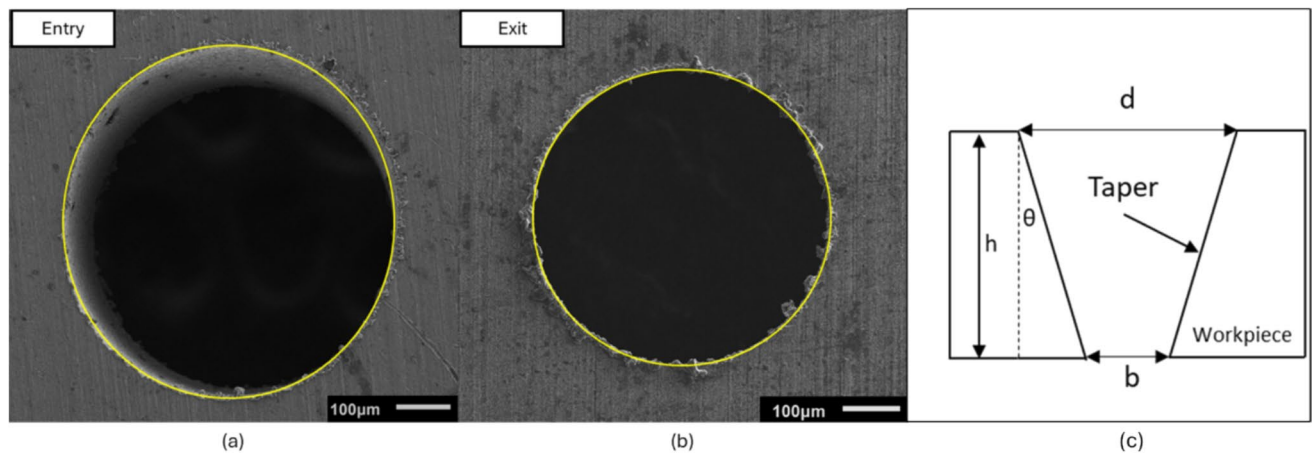


Fig. 3 Diameter (yellow contour) and taper angle measurement of μ EDM holes from the SEM images of copper workpiece. **a** Entry diameter. **b** Exit diameter. **c** Taper angle

the total number of laser passes, affecting the cumulative material removal and taper formation. The experiments were carried out on stainless steel workpieces with a thickness of 600 μm . A full factorial experiment was performed using laser powers of 10%, 50%, and 90%, scanning speeds of 10, 100, and 1000 mm/s, and loop counts of 75, 150, and 225. In a separate study, the programmed diameter was varied with values of 80, 180, and 280 μm .

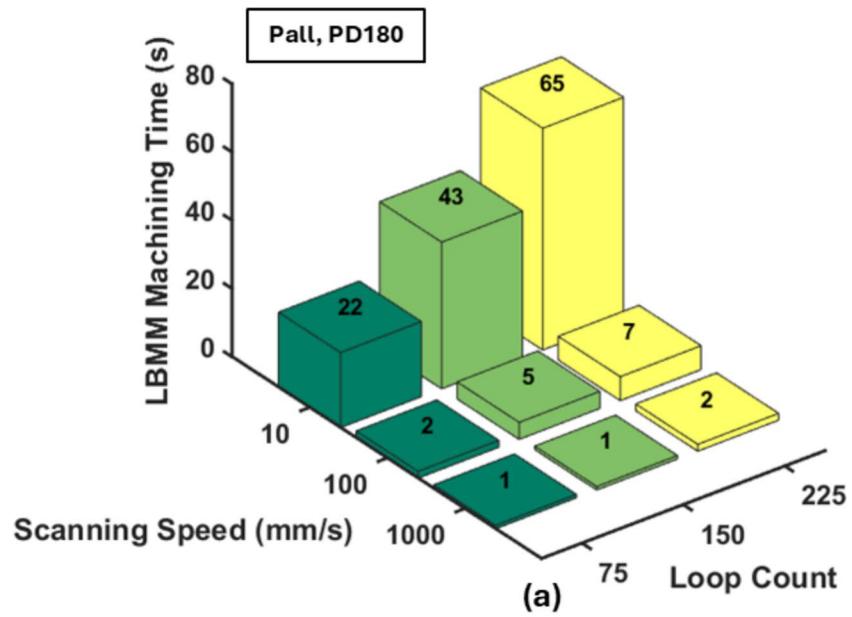
Figure 4a illustrates the effect of scanning speed and loop count on the LBMM processing time for laser powers of 10%, 50%, and 90%, with a programmed diameter of 180 μm . It can be observed that processing time decreases significantly with increasing scanning speed, as higher speeds reduce the duration of laser exposure per pass. Higher loop counts, on the other hand, lead to longer laser machining times. For example, at a low scanning speed of 10 mm/s, increasing the loop count from 75 to 225 results in processing times rising from 22 to 65 s. Therefore, a loop count of 75 was selected for this study. Moreover, although very high scanning speeds, such as 1000 mm/s, reduce processing time, they were not chosen because, as shown in Fig. 4b, they result in smaller entry diameters, which would increase the overall machining time in the subsequent μ EDM finishing process and will be discussed later. Figure 4b depicts the effect of the power and scanning speed at a fixed loop count of 75 and LBMM programmed diameter of 180 μm . At high power (90%), the largest entry diameters are achieved at low scanning speeds (225 μm at 10 mm/s), with sufficiently large exit diameters to ensure proper debris flow. Ideally, the large entry and exit diameters are preferred, as these through-holes facilitate efficient flushing (during the μ EDM finishing process), which is critical for successful hybrid machining. Furthermore, the LBMM programmed diameter has a significant impact on the final hybrid machining performance due to the formation of the recast layer.

Importantly, the LBMM entry diameter, including the recast layer, must remain below 300 μm , which corresponds to the μ EDM electrode size, to ensure that the recast layer can be fully removed during the subsequent μ EDM finishing process. Figure 4c shows the variation of LBMM entry diameter (including and excluding recast layer) and hybrid machining time for different programmed diameters, at 90% laser power, 10 mm/s scanning speed, and a loop count of 75. At a programmed diameter of 80 μm , the hybrid machining time remains relatively long (30 min), similar to the machining time of pure μ EDM. In contrast, a programmed diameter of 280 μm results in the fastest hybrid machining time (4 min) and the highest LBMM entry diameter, as the larger diameter improves debris flushing efficiency. However, the LBMM entry diameter, along with the recast layer, is 423 μm , which is larger than the 300- μm electrode used in this study. This leaves part of the recast layer unremoved from the edge of the final hole, resulting in poor hole quality. A typical morphological comparison of the final hole after the hybrid process is illustrated in Fig. 4c, showing the differences between programmed diameters of 180 and 280 μm . The 180- μm hole exhibits complete removal of the recast layer from the edge of the finished hole, while the 280- μm hole still retains some recast material. Therefore, a programmed diameter of 180 μm was selected, as it provides a reasonable machining time of 7 min while maintaining acceptable hole quality. To summarize, the selected LBMM parameters for efficient hybrid machining are 90% laser power, 10 mm/s scanning speed, 75 loops, and a 180- μm programmed diameter. These settings provide sufficient entry and exit diameters for effective flushing, complete removal of the recast layer formation, and balance machining efficiency with hole quality.

Fluence, also known as energy density, refers to the laser energy applied per unit area (J/cm^2) during the LBMM process, and cumulative fluence represents the

Fig. 4 **a** Study of machining time with scanning speed and loop count. Similar trend is observed for all laser power setting. **b** Effect of laser power and scanning speed on the entry and exit diameters of the LBMMed holes with fixed loop count and programmed diameter. **c** Effect of programmed diameter on the entry, recast layer size, and hybrid machining time with fixed laser power, scanning speed, and loop count. **d** Effect of cumulative laser fluence at different laser power on the LBMMed hole's taper angle. **e** Effect of laser pulse number at different laser power on the LBMMed hole's taper angle

LBMM Machining Time vs Scanning Speed and Loop Count



Entry and Exit Diameter Vs Power and Scanning Speed

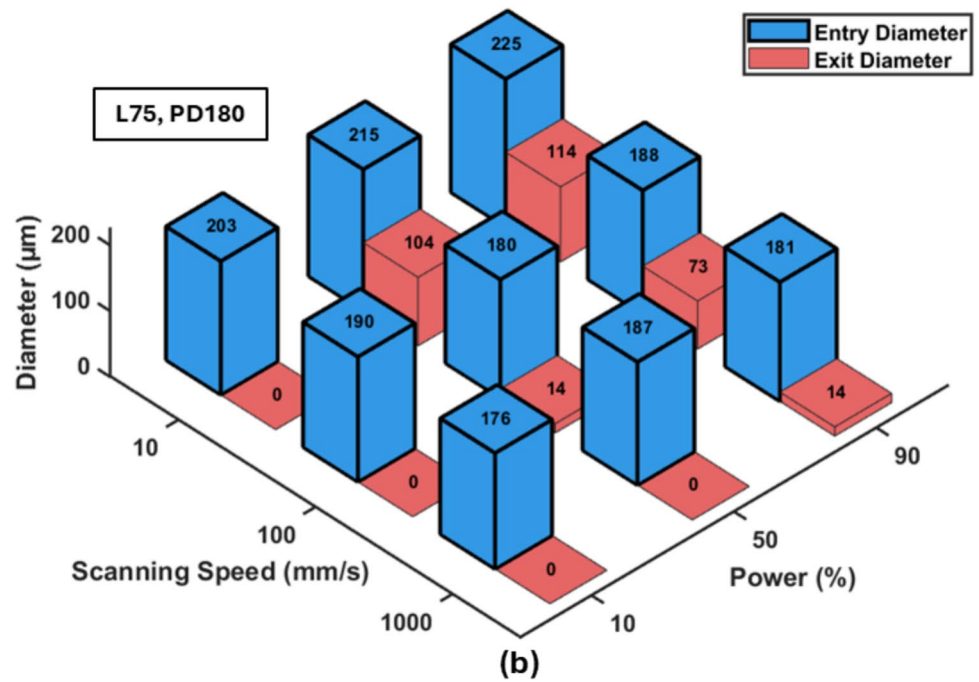
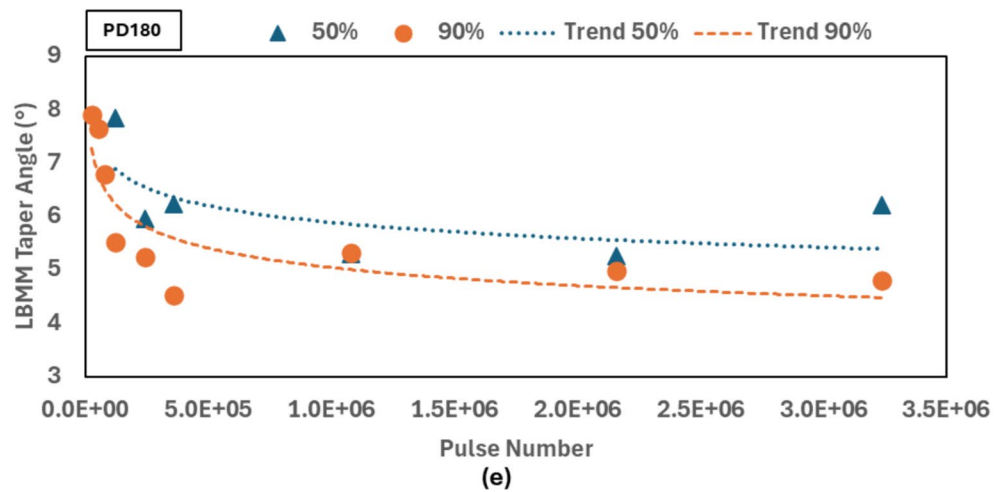
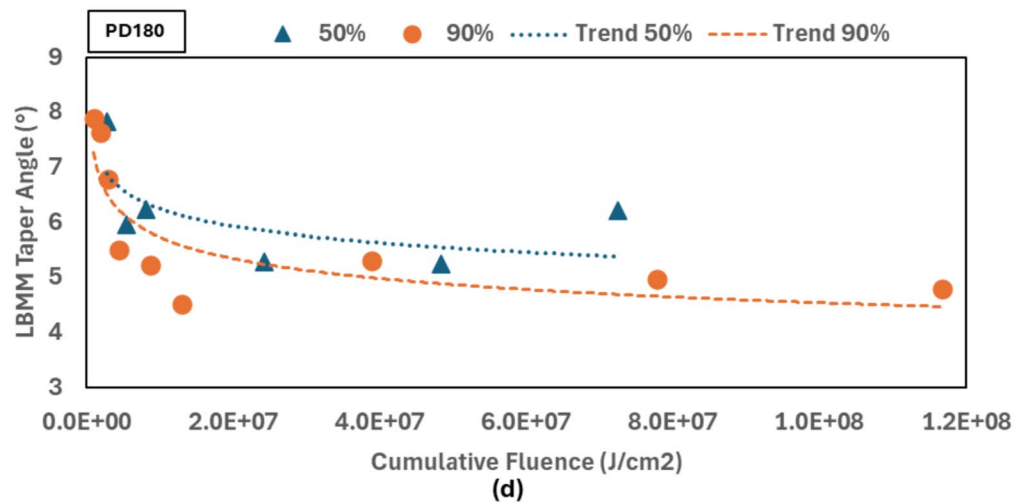
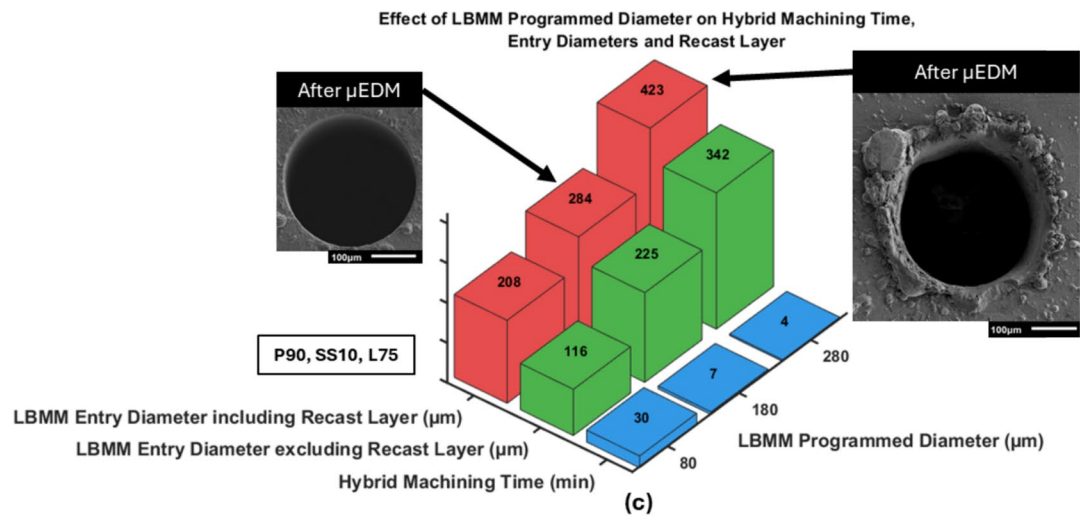


Fig. 4 (continued)



total energy delivered to the material over the entire number of laser pulses. In this study, the cumulative fluence was varied by adjusting the laser power, scanning speed, and loop count. In addition, the pulse number was determined from the laser processing time and laser frequency. The equation for the cumulative fluence is shown in Eq. (2). The effect of the cumulative fluence and laser pulse number on the LBMMed hole's taper angle is shown in Fig. 4d,e, respectively. It should be noted that only LBMMed holes that pierced through were plotted in the figures. LBMMed holes that did not pierce through were excluded, as their taper angle could not be measured. Specifically, at 10% laser power, none of the holes pierced through. At 50% power, the hole at a scanning speed of 225 mm/s did not pierce through. At 90% power, all holes successfully pierced through. It can be inferred from Fig. 4d,e that the taper angle decreases with increasing cumulative fluence and pulse number. At both 50% and 90% laser power, a steep reduction in taper angle is observed at lower fluence and pulse numbers, followed by a gradual decrease that approaches a near-constant value of around 4–5° at higher inputs. Across the entire range, the 90% laser power condition tends to produce lower taper angles compared to 50% power, indicating improved hole quality at higher power settings. This suggests that higher cumulative fluence and larger pulse numbers reduce the diameter difference between the entry and exit holes, thereby minimizing tapering in LBMMed holes. Therefore, 90% laser power was selected in this study, as it resulted in the minimal taper angle along with the largest entry and exit diameters. In the subsequent section, we present the compensation strategy developed to mitigate the effect of the initial taper induced by the LBMM process through subsequent μ EDM finishing, which constitutes the primary focus of this study.

$$\text{Cumulative fluence, } F_{\text{cumulative}} = \frac{P_{\text{App}} \cdot t}{A} \left[\frac{\text{J}}{\text{cm}^2} \right] \quad (2)$$

where P_{App} is the applied laser power (W), t is the processing time (s), and A is the spot area (cm^2).

3 Results and discussions

This section presents the results and discussion on tool wear analysis for the μ EDM in the hybrid LBMM– μ EDM process, with a focus on characterizing axial and radial wear lengths across different workpiece material types and workpiece thicknesses. Additionally, this section outlines a compensation method for tool wear to ensure the fabrication of accurate and consistent microhole arrays.

3.1 Comparison of tool wear in hybrid LBMM– μ EDM and pure μ EDM

Figure 5a,b illustrates the evolution of electrode geometry during continuous machining on stainless steel material with a thickness of 600 μm for the pure μ EDM and hybrid LBMM– μ EDM processes, respectively. It can be inferred from Fig. 5a that the electrode subjected to successive pure μ EDM experiences more pronounced axial wear while largely maintaining its diameter. In contrast, the electrode used in the hybrid process, as shown in Fig. 5b, develops a tapered, conical shape due to increased radial tool wear length.

This manuscript attempts to explain the different tool wear characteristics observed experimentally for pure μ EDM and the LBMM– μ EDM process. Figure 6a–d illustrates the spark discharge regions on electrodes during pure μ EDM and hybrid laser-based μ EDM processes. In Fig. 6a, in pure μ EDM, most of the spark discharge occurs at the bottom surface of the electrode as it is positioned above the workpiece. This uniform discharge ensures consistent wear at the bottom. In Fig. 6b, as the electrode machines within the workpiece, the spark discharge is distributed across both the bottom surface and the sidewalls of the electrode. This balanced discharge helps maintain the electrode's shape, minimizes taper, and ensures precise machining.

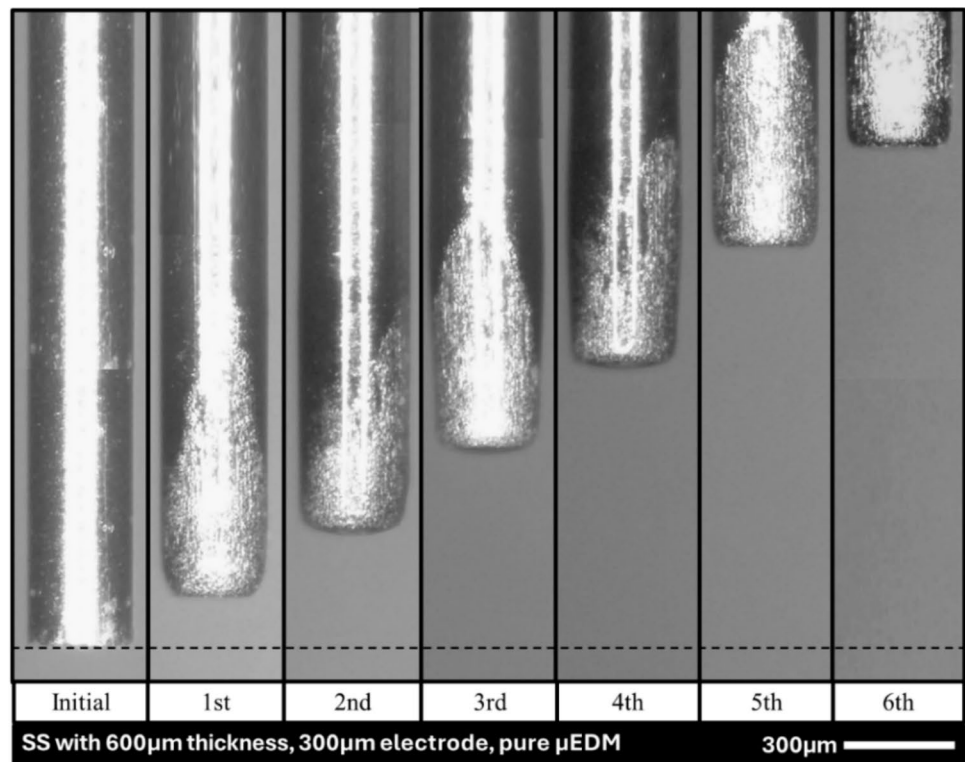
For the hybrid laser-based μ EDM process in Fig. 6c, when the electrode is positioned above the workpiece before penetration, the spark discharge is localized to a small region at the bottom corner of the electrode, with minimal activity at the center of the bottom surface. In Fig. 6d, during machining within the workpiece, the spark discharge is concentrated along the sidewalls of the electrode, promoting radial wear length. This limited discharge activity in the center reduces axial wear, resulting in distinct machining characteristics compared to the pure μ EDM process.

3.2 Comparison of tool wear on different workpiece thickness and material

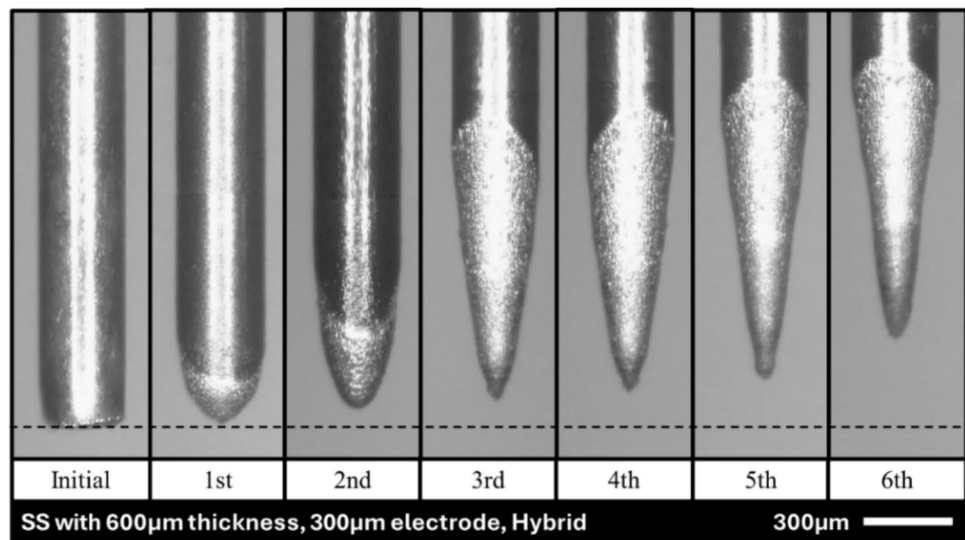
This study investigates the variation in tool wear characteristics when machining stainless steel and copper workpieces with thicknesses of 600 and 200 μm , using a 300- μm electrode in the hybrid LBMM– μ EDM process. The evolution of electrode geometry during continuous machining is depicted in Figs. 5 and 7. Based on visual inspection, it can be inferred from the figures that radial wear length is more significant on stainless steel compared to copper. Furthermore, insignificant or no axial wear was observed on the 200- μm thick workpiece (for both copper and stainless steel), in contrast to the 600- μm thick workpiece.

For in-depth analysis, the axial and radial wear lengths during the hybrid LBMM– μ EDM, as well as the microhole's

Fig. 5 Evolution of electrode geometry in continuous machining for **a** pure μ EDM and **b** hybrid LBMM- μ EDM (stainless steel workpiece of 600- μ m thickness with 300- μ m electrode)



(a)

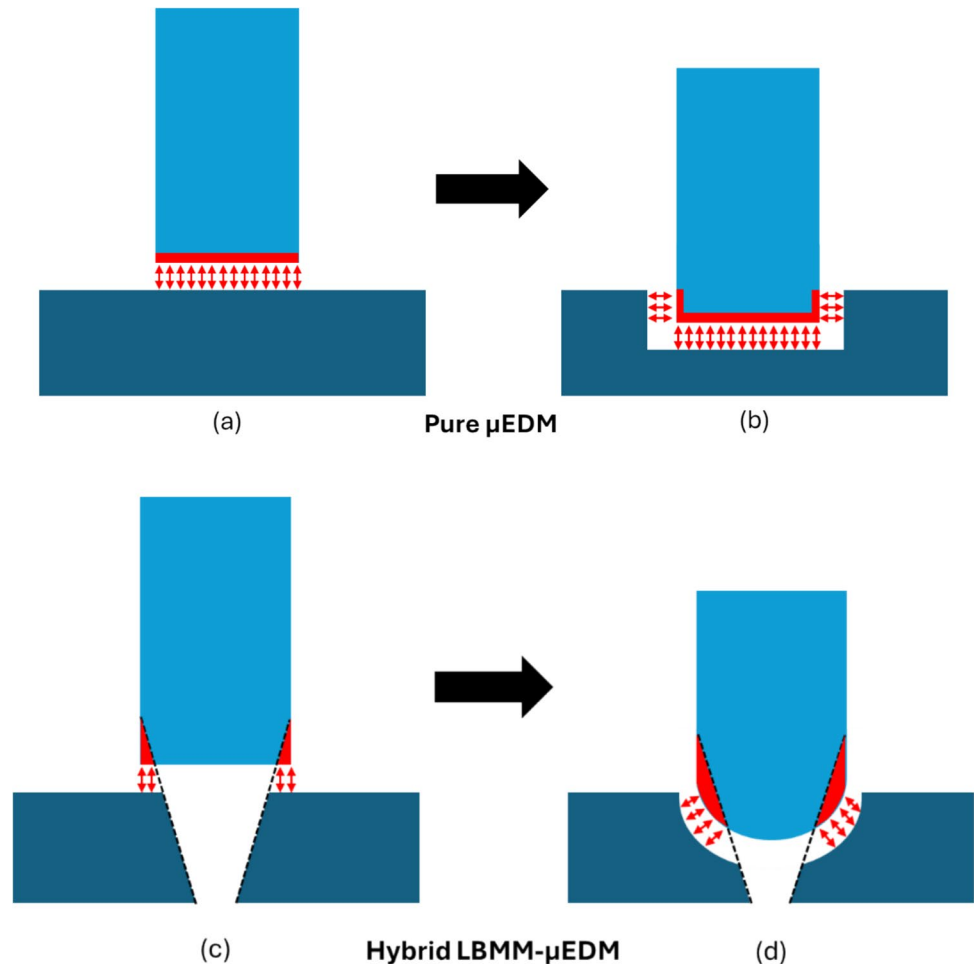


(b)

taper angle measurement, are summarized in Fig. 8a–c. Apart from the absence of axial wear on the 200- μ m thick workpiece, stainless steel recorded a higher average axial tool wear compared to the copper workpiece in the 600- μ m thick workpiece, as shown in Fig. 8a. The reason for this is that the μ EDM processing time for copper is much shorter compared to stainless steel, as shown in Fig. 8d. The presence of axial wear in the 600- μ m thick workpieces (both stainless steel and copper) but its absence in the 200- μ m thick workpieces in Fig. 8a can be attributed to the

differences in machining conditions and spark distribution, as explained in Fig. 6. Thicker workpieces, such as the 600- μ m ones, require deeper machining, leading to prolonged spark exposure probability on the bottom surface of the electrode, which promotes axial wear. In contrast, the shallower penetration required for the 200- μ m thick workpieces reduces the chance of spark exposure on the electrode's bottom surface, effectively almost eliminating axial wear. However, the radial wear length increases continuously with the increase in the hole sequence number, as shown in Fig. 8b

Fig. 6 Spark discharge regions in pure μ EDM and hybrid LBMM- μ EDM processes. **a** Electrode positioned above the workpiece before penetration in pure μ EDM. **b** Electrode machining within the workpiece in pure μ EDM. **c** Electrode positioned above the workpiece before penetration in hybrid LBMM- μ EDM. **d** Electrode machining within the workpiece in hybrid LBMM- μ EDM



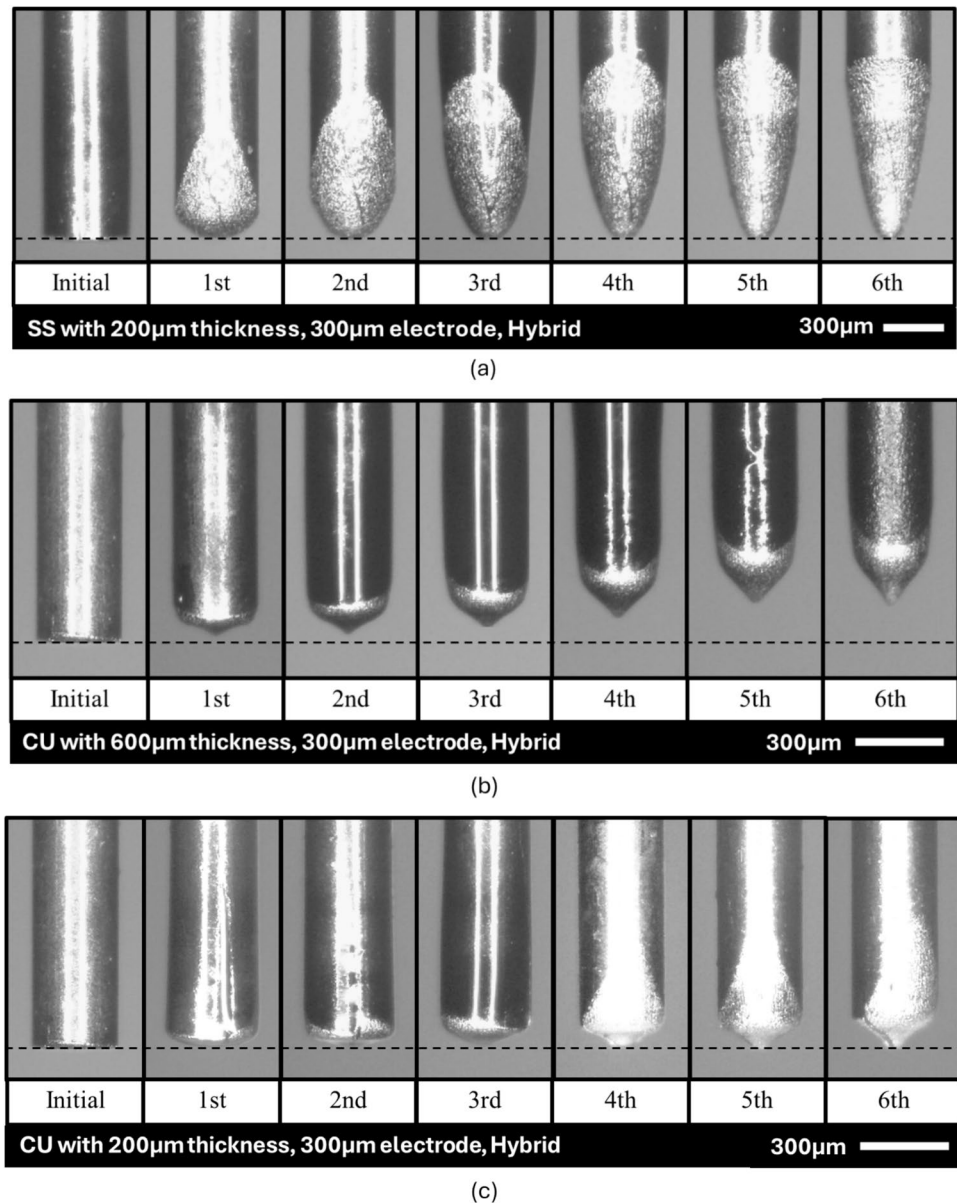
for both materials and thicknesses. Stainless steel, for both thicknesses, shows a higher radial wear length compared to copper. In μ EDM machining, copper is widely recognized as an easier material to machine compared to stainless steel [41]. The higher radial wear length observed in stainless steel compared to copper is due to the higher machining time, as depicted in Fig. 8d. The longer interaction time of stainless steel with the electrode contributes to increased tool wear. From a material properties perspective, stainless steel has lower thermal conductivity and a higher melting point than copper, which causes localized heat accumulation and increases the likelihood of wider spark dispersion around the electrode edges, resulting in greater radial wear. Additionally, copper's lower electrical resistivity enables more efficient and frequent spark discharges, resulting in a higher discharge rate and faster material removal. In contrast, the higher electrical resistivity of stainless steel leads to a lower discharge rate, requiring prolonged spark activity to achieve the same depth, thereby increasing tool wear, especially along the radial direction [42].

The graph of machining time and discharge pulse number, as shown in Fig. 8d,e, highlights that the 600- μ m thick

workpieces have significantly longer machining times and higher discharge pulse numbers compared to the 200- μ m thick workpieces. This indicates that the deeper machining required for the 600- μ m thickness involves more prolonged spark activity, which contributes to the observed tool wear, axially and radially. However, the increase in machining time is not proportional to the increase in thickness. In hybrid LBMM- μ EDM processes, this nonlinear scaling is influenced by several factors. During μ EDM, deeper cavities reduce flushing efficiency, causing debris accumulation and unstable discharges, which slow down the MRR [43]. As the machining depth increases, the risk of short circuits and arcing also rises, resulting in more frequent pauses in the process. Moreover, the workpiece thickness has a significant effect on the resulting cut quality during laser machining [44]. This is due to increased laser energy loss as the beam penetrates deeper into the material, where scattering, surface reflection, and thermal diffusion become more pronounced. These combined effects make the machining time grow at a faster rate than the workpiece thickness.

This radial tool wear length directly impacts the tapering of the microhole array, as clearly shown in Fig. 8c. For both

Fig. 7 Evolution of electrode geometry in continuous machining for hybrid LBMM- μ EDM for **a** SS with 200- μ m thickness, **b** Cu with 600- μ m thickness, and **c** Cu with 200- μ m thickness (using 300- μ m electrode)



thicknesses of stainless steel, the taper angle increased linearly after successive machining, while copper maintained a consistently low taper angle. Axial wear can be easily compensated for by performing surface detection before machining each hole. However, radial wear length must be compensated for by adjusting the programmed machining depth. In these experiments, the programmed machining depth was set to a constant value for each successive operation: 1000 μ m for the 600- μ m thick material and 600 μ m for the 200- μ m thick material, leaving an additional 400 μ m to compensate for radial wear. This compensation was sufficient for the copper workpiece, where the maximum radial wear recorded was 335 μ m, as shown in Fig. 8b, resulting in low taperness in the microholes, as seen in Fig. 8c. However, this was insufficient for the stainless steel material, as the

radial wear length exceeded 400 μ m. To address this issue, a dynamic compensation strategy has been proposed, which will be discussed in the next section.

3.3 Compensation strategy and verification

This section proposes an offline compensation method to mitigate the tapering effect in the machining of successive microhole arrays in hybrid LBMM- μ EDM. Axial wear is compensated by performing surface detection before machining each hole. However, radial wear length must be compensated by adjusting the programmed machining depth. It is important to clarify that the aim of this study was not to reduce tool wear itself but rather to study its characteristics and propose a compensation strategy to achieve high-quality

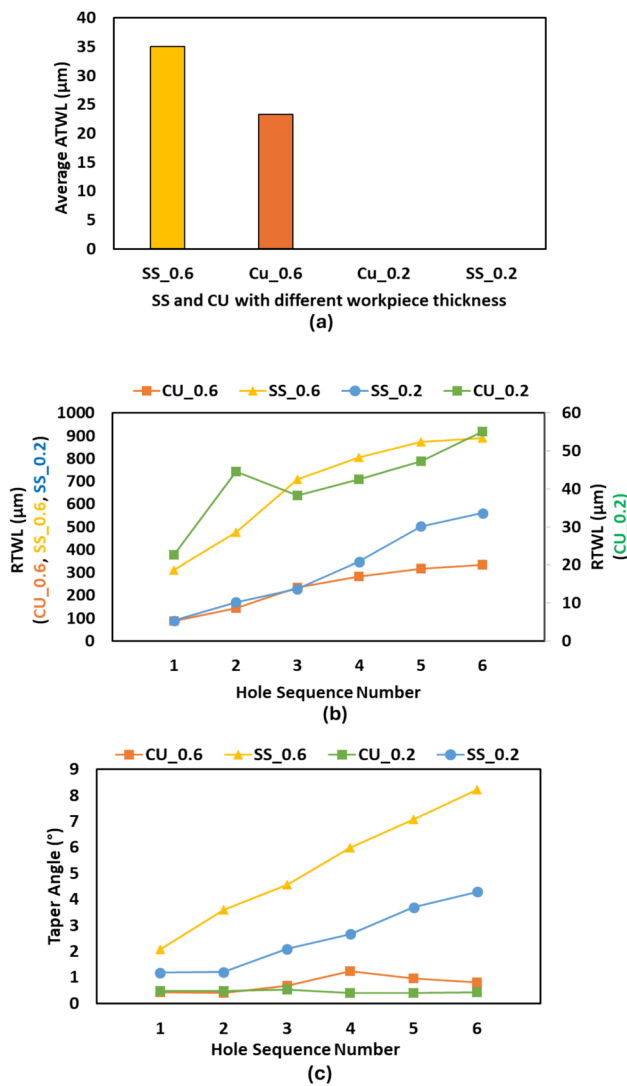


Fig. 8 Comparison of hybrid LBMM-μEDM performance between stainless steel and copper in 600-μm thickness (SS_0.6 and Cu_0.6) and 200-μm thickness (SS_0.2 and Cu_0.2), with 300-μm electrode diameter in terms of **a** average axial tool wear length (ATWL), **b** radial tool wear length (RTWL), **c** microholes' taper angle, **d** machining time, and **e** discharge pulse number

holes with reduced taper angle and efficient machining time. By increasing the programmed machining depth using the proposed dynamic compensation formula, the negative effects of both RTWL and ATWL on the final hole geometry can be significantly minimized. This approach enables more uniform hole profiles and enhances dimensional consistency, despite the inevitable occurrence of tool wear during the process. Moreover, more detailed studies on the effect of laser parameters in sequential LBMM and μEDM processes have been conducted in previous work [45].

Using the experimental data, the radial wear length can be predicted and incorporated into the programmed machining depth calculation. Figure 9a–c illustrates the electrode

position during μEDM in the hybrid process with a tapered electrode at different stages: initially, after surface detection, before exiting the workpiece, and after exiting the workpiece.

Initially, the tapered electrode performs surface detection to eliminate the axial wear from the previous hole machining, as shown in Fig. 9a. If the programmed machining depth d is set equal to the workpiece thickness t , the hole will become tapered due to the taper of the electrode, as illustrated in Fig. 9b. To prevent this, the programmed machining depth must be adjusted to account for both the workpiece thickness and radial wear length, with a safety factor f . This factor was introduced to ensure that machining is consistently carried out within the nontapered portion of the electrode, considering several sources of uncertainty in the process. The selected value compensates for uncertainties in radial tool wear length measurement, nonuniform workpiece thickness, surface detection accuracy, and CNC stage positioning, which has a specified tolerance of $\pm 15 \mu\text{m}$.

Although the value of $f=1.2$ was not derived through formal optimization, it was conservatively selected to provide a sufficient safety margin for consistent and reliable through-hole machining. Using a lower value could result in insufficient depth, incomplete breakthrough, or an increased failure rate due to the accumulation of positional and measurement errors. On the other hand, selecting a higher safety factor would unnecessarily increase machining time and may lead to excessive overcutting. Therefore, $f=1.2$ was adopted as a practical compromise between machining reliability and process efficiency. To ensure consistent through-hole machining and compensate for tool wear and process uncertainties, a depth adjustment strategy is introduced. The programmed machining depth is formulated as in Eq. (3):

$$d_n = f \times (t + RTWL_n) \quad (3)$$

where d_n is the programmed machining depth in micrometer with respect to the hole sequence number n , f is the safety factor, t is the workpiece thickness, and $RTWL_n$ is the radial tool wear length. The radial tool wear length $RTWL_n$ was linearly approximated based on the experimental data, providing a predictive model for adjusting the programmed machining depth, as illustrated in Fig. 9d. Table 2 summarizes the equation for programmed machining depth for stainless steel and copper, considering workpiece thicknesses of 600 and 200 μm, using a 300-μm electrode.

The linearized radial tool wear length (RTWL) equation varies based on both the workpiece thickness and the material type, as summarized in Table 2. However, for a given material, the coefficients and constants of the RTWL equations can be estimated through linear interpolation between two known thickness values. For instance, Table 2 presents RTWL equations for stainless steel (SS) at thicknesses of

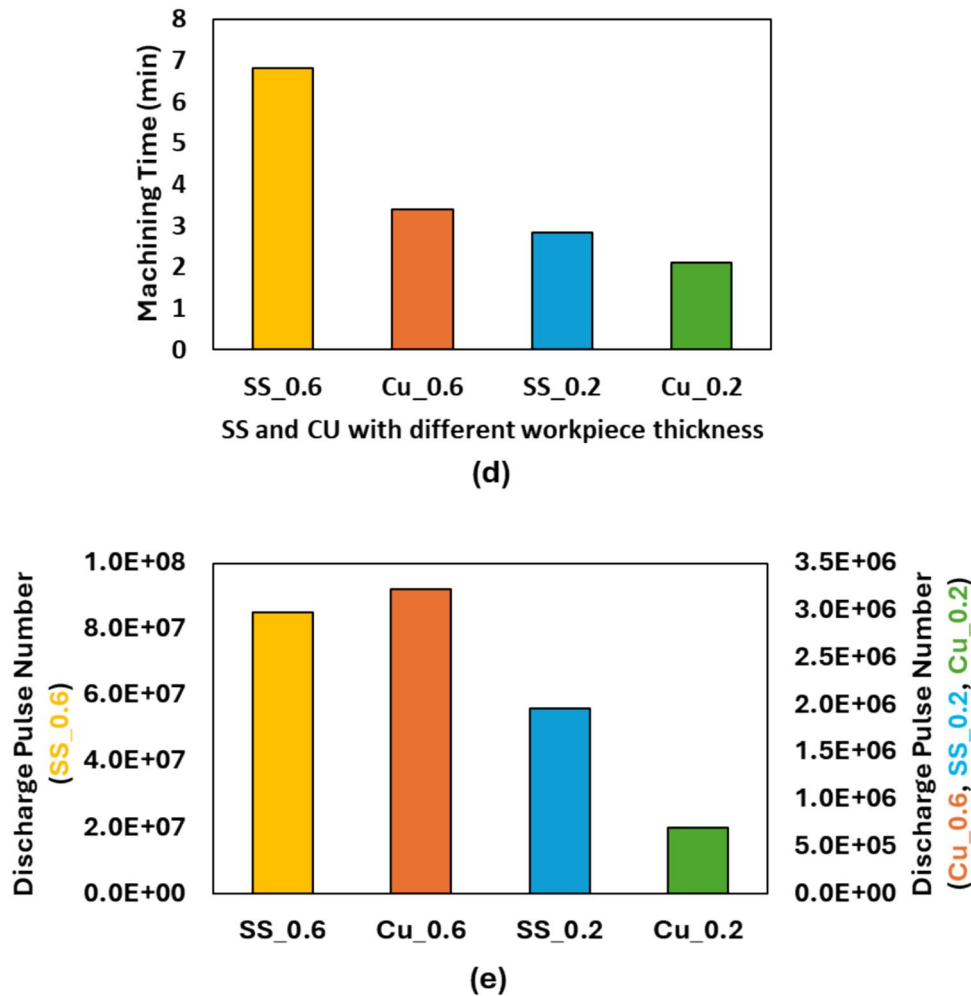


Fig. 8 (continued)

200 and 600 μm . To estimate the RTWL equation for SS at any intermediate thickness within this range, linear interpolation of the coefficient and constant can be employed. The accuracy of the interpolated RTWL equation can be improved by reducing the gap between the experimentally measured thickness values. Another constraint is the available length of the electrode mounted on the collet, which limits the maximum achievable machining depth. Additionally, the model assumes a limited number of holes per electrode, since progressive wear will eventually require repositioning or replacement of the electrode. It is important to highlight that the current RTWL model is specific to the tested material and electrode diameter and therefore may not be directly applicable to other material–electrode combinations. To improve generalizability, a more comprehensive, data-driven approach is recommended. This would involve building a large data set encompassing various workpiece materials, electrode diameters, and machining parameters. Such a dataset could support the development of a universal

model using predictive algorithms or machine learning techniques, enabling accurate RTWL estimation across a wider range of conditions.

To verify the compensation strategy, the same experiment was conducted using stainless steel with a thickness of 600 μm and a 300- μm electrode diameter but with the compensation method applied. The safety factor f was set to 1.2. Table 3 compares the programmed machining depth with and without compensation, emphasizing the dynamic adjustment of the programmed depth. From the table, it can be observed that compensation was only possible for the first hole, as the machining depth exceeded both the total radial wear length and the workpiece thickness. However, by employing the proposed compensation method, all radial wear lengths are effectively compensated, as indicated by the green text.

Figure 10 presents a morphological comparison of micro-hole arrays produced using three different approaches: pure μEDM , hybrid machining without compensation, and

Fig. 9 The electrode position during μ EDM in the hybrid process with a tapered electrode. **a** Initial position after surface detection. **b** Before exiting the workpiece. **c** After exiting the workpiece. **d** Linear approximation of RTWL for stainless steel with a 600- μ m thickness using a 300- μ m electrode

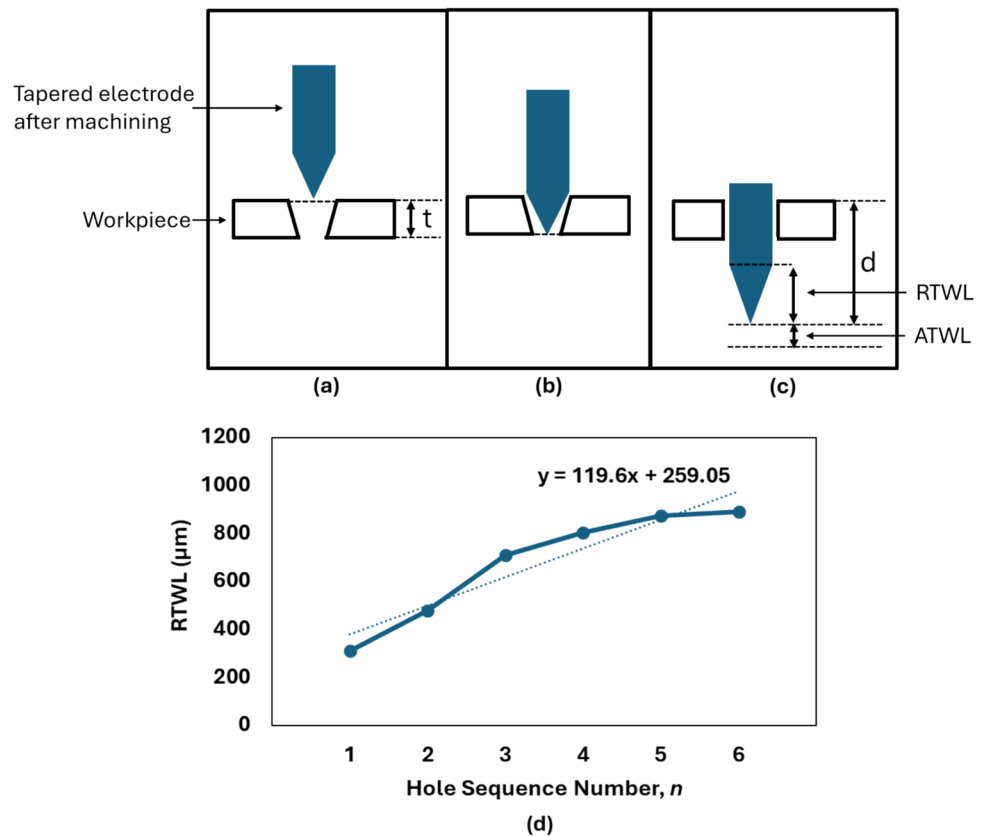


Table 2 Summarized equation for programmed machining depth for stainless steel and copper, considering workpiece thicknesses of 600 and 200 μ m, using a 300- μ m electrode. (t is workpiece thickness, d_n is programmed machining depth, f is the safety factor, and n is the hole sequence number)

t (μ m)	Stainless steel	Copper
200	$d_n = f \times (99.156n + 169.928)$	$d_n = f \times (6.0012n + 218.759)$
600	$d_n = f \times (119.6n + 859.05)$	$d_n = f \times (51.529n + 653.047)$

hybrid machining with compensation. It is evident that pure μ EDM produces microholes with a minimal taper angle. However, this comes at the expense of longer machining time. To support this observation, Fig. 11 provides a quantitative comparison of machining performance in terms of taper angle and machining time, based on three repeated trials ($n = 3$), with error bars representing the minimum and maximum values. As shown in Fig. 11b, the pure μ EDM approach results in the longest machining time. This trade-off highlights the advantage of adopting LBMM- μ EDM, which optimally balances machining speed and precision by leveraging the strengths of both processes. Moreover, as shown in Fig. 11, it is worth noting that the pure μ EDM process exhibits greater variability in machining time, while the

hybrid process without compensation shows higher variability in taper angle, as indicated by the wider range between the minimum and maximum values represented by the error bars.

Furthermore, Fig. 10 also demonstrates that hybrid machining without compensation exhibits a noticeable tapering issue, particularly evident in the exit holes, where the hole size progressively decreases throughout the machining sequence. This phenomenon leads to an increase in taper angle with successive machining, as illustrated in Fig. 11a. In contrast, hybrid machining with compensation effectively addresses this tapering problem, resulting in a lower taper angle that is comparable to that of pure μ EDM. On average, the compensation method results in a $7\times$ reduction in taper angle compared to the hybrid process without compensation. Additionally, the taper angle in hybrid machining with compensation is $2\times$ smaller compared to pure μ EDM.

In addition, hybrid machining with compensation exhibits only a slight increase in machining time compared to hybrid machining without compensation. This is primarily due to the need for deeper machining during the compensation process, which adds to the overall machining time. However, both hybrid machining methods are significantly faster than pure μ EDM, as shown in Fig. 11b. On average,

Table 3 Programmed machining depth for stainless steel of 600- μm thickness with 300- μm electrode diameter, with and without compensation (green text: compensated)

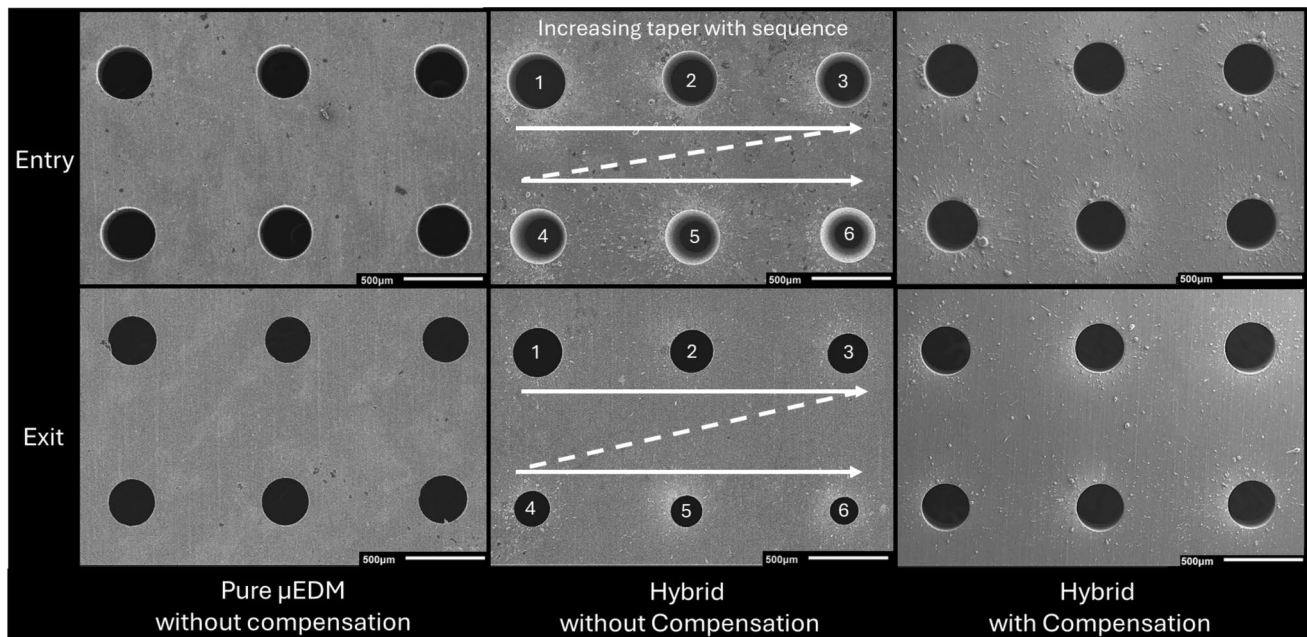
Hole sequence number, n	RTWL + Workpiece Thickness (μm)	Programmed machining depth, d_n (μm)	
		Without Compensation	With Compensation
1	912	1000	1174
2	1076	1000	1318
3	1309	1000	1461
4	1404	1000	1605
5	1475	1000	1748
6	1491	1000	1892

the hybrid methods achieve a $4\times$ reduction in machining time compared to pure μEDM .

In the hybrid process, residual spatters resulting from LBMM are still visible, as shown in Fig. 10. This is primarily because the μEDM electrode diameter is insufficient to completely remove the spatter during machining. Potential solutions include using a larger μEDM electrode diameter or

reducing the size of the LBMM hole to ensure better overlap during the finishing process. Additionally, chemical etching has been identified as an effective postprocessing method to further eliminate residual spatter from LBMM and enhance surface quality, as demonstrated in previous studies [46].

These findings confirm that the compensation method effectively mitigates the tapering issue in the successive

**Fig. 10** SEM images showing the morphological comparison of microhole arrays produced by pure μEDM , hybrid without compensation, and hybrid with compensation on a 600- μm thick stainless steel workpiece, highlighting both entry and exit sides for comparison

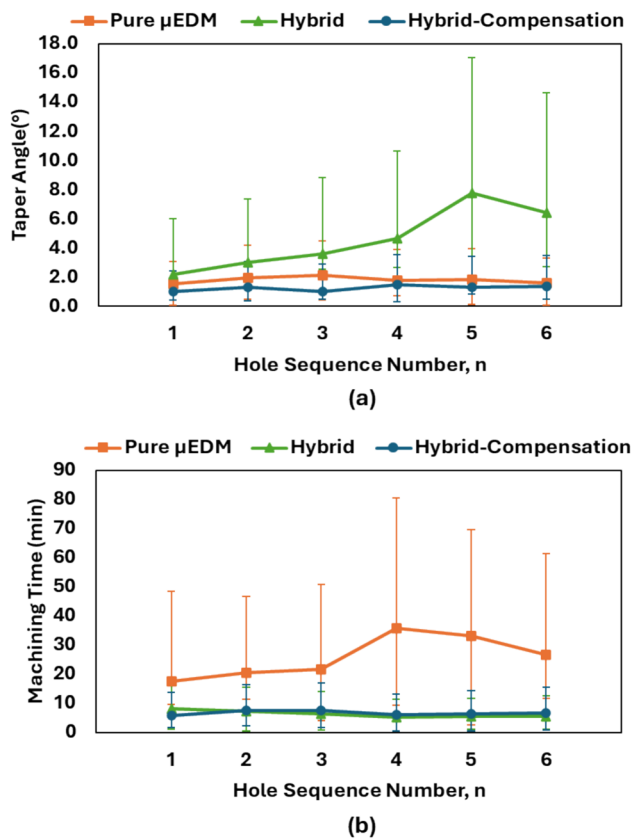


Fig. 11 Comparison of machining performance on 600- μ m thick stainless steel between pure μ EDM, hybrid, and hybrid with compensation, in terms of **a** taper angle and **b** machining time. Error bars represent the minimum and maximum values observed based on three repeated trials ($n=3$)

machining of microhole arrays by accurately compensating for radial tool wear length.

4 Conclusion

The tool wear analysis for the sequential hybrid LBMM and μ EDM process is essential to ensure the practical, consistent, and high-quality fabrication of microhole arrays. As the tool becomes more tapered with each machining step, it can lead to tapered microholes. Key findings from the analysis are as follows:

- The hybrid LBMM- μ EDM process exhibited more pronounced radial tool wear length compared to the pure μ EDM process, while the pure μ EDM process exhibited higher axial tool wear length.
- Stainless steel demonstrated higher radial tool wear length than copper, and thicker workpieces increased axial wear.

- A compensation strategy has been proposed and successfully tested to mitigate the impact of taperness and improve the quality of successive microhole array machining by adjusting the programmed machining depth to account for radial tool wear length, ensuring consistent machining quality.
- On average, the hybrid process with compensation results in a $7\times$ reduction in taper angle compared to the hybrid process without compensation. Moreover, the hybrid process with compensation achieves a $4\times$ reduction in machining time compared to pure μ EDM.

By effectively compensating for tool wear, the sequential hybrid LBMM- μ EDM process enables the fabrication of microhole arrays with the same high quality as pure μ EDM but at a $4\times$ faster machining rate. This advancement enhances productivity, precision, and sustainability in microfabrication.

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Author contribution WABWA is the research student associated with this work. He conducted all experiments, collected and analyzed the data, and prepared the manuscript. TS served as the project supervisor, providing guidance throughout the research and offering valuable input for manuscript preparation.

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Declarations

Competing interests The authors declare no competing interests.

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