Effect of laser parameters on sequential laser beam micromachining and micro electro-discharge machining

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Abstract
Laser beam micromachining (LBMM) and micro electro-discharge machining (μEDM) based sequential micromachining technique, LBMM-μEDM, has drawn significant research attention to utilize the advantages of both methods, i.e., LBMM and μEDM. In this process, a pilot hole is machined by the LBMM, and subsequently finishing operation of the hole is carried out by the μEDM. This paper presents an experimental investigation on the stainless steel (type SS304) to observe the effects of laser input parameters (namely, laser power, scanning speed, and pulse frequency) on the performance of the finishing technique, that is, the μEDM in this case. The scope of the work is limited to 1-D machining, i.e., drilling microholes. It was found that laser input parameters mainly scanning speed and power influenced the output performance of μEDM significantly. Our study suggests that if an increased scanning speed at a lower laser power is used for the pilot hole drilling by the LBMM process, it could result in significantly slower μEDM machining time. On the contrary, if the higher laser power is used with even the highest scanning speed for the pilot hole drilling, then μEDM processing time was faster than the previous case. Similarly, μEDM time was also quicker for LBMMed pilot holes machined at low laser power and slow scanning speed. Our study confirms that LBMM-μEDM-based sequential machining technique reduces the machining time, tool wear, and instability (in terms of short circuit count) by a margin of 2.5 x, 9 x, and 40 x, respectively, in contrast to the pure μEDM process without compromising the quality of the holes.

Keywords Sequential micromachining · Laser beam micromachining · Micro electro-discharge machining · LBMM · μEDM

1 Introduction
Micromachining is one of the key technologies that has been developed to meet the challenges posed by the requirement of product miniaturizations. Various micromachining techniques are used to create intricate parts in a dimensional range of less than 100 μm with tolerance and average surface roughness of sub-micrometer in electronics, aerospace, biomedical, MEMS (micro electromechanical system), and optical industries [1]. Broadly, micromachining can be classified into two major categories, namely, beam-based and tool-based micromachining. Laser beam, ion beam, photolithography, and electron beam micromachining are examples of beam-based micromachining. In contrast, micro electro-discharge machining, micro electrochemical machining, micro-milling, etc. are examples of tool-based micromachining [2, 3]. According to Chavoshi et al. [1], micromachining has successfully produced complex microstructure (both 2D and 3D) on a broader range of materials with a high level of precision, thus bridging the gap between macro- and microdomain.

Laser beam micromachining (LBMM) is a beam-based machining process that uses thermal energy to carry out the material removal to produce the desired cavity on the workpiece. Due to conventional machining methods’ various limitations, LBMM is widely used for drilling, cutting, milling, grooving, turning, etc. [4]. LBMM is a quick machining process; however, its ability of fast material removal comes with the price of the heat-affected zone (HAZ) [4] and forms inaccuracy on the machined feature; i.e., laser micromachining causes the structures to be
tapered [5]. The use of ultrashort pulse laser machining may counteract the problem of HAZ. Ancona et al. [6] used an ultrashort laser beam (1030 nm) with a pulse on time of 800 fs to 19 ps and a repetition rate of 200 to 300 kHz to drill stainless steel plate (thickness = 0.5mm). Yet the holes resulted in the research [6] had a low circularity and substantial recast layer. Gruner et al. [7] used 1030 nm laser beam with 220 fs pulse on time and frequency 10 kHz to 1 MHz to drill thru 0.3 mm stainless steel. The morphological study [7] suggests that the circularity of the holes were somewhat inadequate. Barthels et al. [8] also carried out laser drilling of 10μm stainless steel sheet using 900 fs laser (515 nm) with a repetition frequency 100 kHz. The microscopic study suggests that the holes are not free from the heat-affected zone [8]. However, researchers also reported that with optimum processing condition, the ultrashort laser can produce precise microholes with reasonable dimensional accuracy and reduced HAZ and recast layer [9]. Yet, one of the major bottlenecks of the ultrashort pulse laser system is its substantially high initial cost [10]. Further, this type of laser is relatively inefficient when used for thicker material [10].

Micro electro-discharge machining (μEDM), electrochemical micromachining (EMM), and micro-milling are few examples of tool-based micromachining process. Micro electro-discharge machining (μEDM) is a well-established technology used in the field of microfabrication because of its ability to create features in micrometers domain with high tolerance and excellent structural integrity and quality [11]. It is to note that μEDM is essentially an electrothermal process that utilizes repeated sparks to machine conductive materials such as metals, metallic alloys, and semiconductor with whatsoever hardness [12–14]. The μEDM process is free from chatter effect, mechanical stress, and vibration-related problems due to its inherent noncontact material removal mechanism [15]. Besides, μEDM’ed surface is almost free from HAZ as compared to the LBMM’ed ones.

Nonetheless, μEDM does also have various limitations. The first and foremost is its low material removal rate (MRR) [16]. Apart from low MRR, inevitable spark gap and tool wear also limit the resolution of the features fabricated by μEDM.

Hybrid micromachining processes have drawn particular attention by the researchers to enhance microfabrication technology as a whole [1]. The definition of hybrid machining/micromachining has differed among various researchers. According to Aspinwall et al. and Curtis et al. [17, 18], hybrid machining can be defined as the assimilation of two or more machining processes in a single machine where all the machining methods are utilized simultaneously. Menzies et al. [19] defined hybrid machining as the synergetic integration of two or more machining processes to exploit the advantages of all of them. Both EDM and laser machining have been used in hybrid machining technology. Electrochemical discharge machining (ECDM) is one kind of hybrid machining concept where electrochemical machining and electro-discharge machining are taking place simultaneously. ECDM has the potential to be used for micromachining of nonconductive materials, unlike pure μEDM [20]. Electrical discharge abrasive grinding (EDAG) is another EDM-based hybrid machining that combines conventional grinding and EDM [20]. Vibration-assisted μEDM is another hybrid micromachining approach that has been investigated by numerous researchers [21].

Until recent years, various researchers have reported studies on laser-assisted machining processes. Singh et al. [22] proposed laser-assisted mechanical micromachining for difficult to cut materials. The laser was used to carry out the thermal softening of the hard material, while the mechanical interaction between the cutting tool and the workpiece was in progress. Sun et al. [23] proposed sequential hybrid micromachining combining LBMM and electrochemical micromachining (EMM). They [23] have successfully managed to remove the recast layer machined holes formed during the LBMM process by the subsequent EMM finishing operation. Some other reported laser-assisted machining technologies including laser-assisted turning [24], laser-assisted milling [25], and laser-assisted waterjet machining [26].

Laser-μEDM-based sequential micromachining has also been reported by researchers [27–29]. Li et al. [27] proposed LBMM-μEDM-based micromachining technique to produce fuel nozzle. The proposed approach helped achieve a reduction in drilling time and cost by 70% and 42%, respectively. The production capacity was also increased by 90% without compromising the hole quality than pure EDM drilling. Li et al. [27] also proposed a fixturing mechanism specific to the fuel nozzle to maintain the hole’s alignment accuracy within ±20μm. Kim et al. [28] also investigated micromachining of holes and microstructures using nanosecond pulsed laser and μEDM. The machining time reduction was more than 50% for both micro-drilling and micro-milling operations [28]. Al-Ahmari et al. [29] investigated LBMM-μEDM-based micro-drilling for Ni-Ti-based shape memory alloy (SMA), which helped improve the hole quality to pure LBMM’ed holes. A challenge for LBMM-μEDM sequential machining is the alignment of the μEDM tool on the LBMMed pilot hole, which is not adequately described in the previous research [27–29]. Moreover, to the best of authors’ knowledge, no study has been carried out on how the various parameters of LBMM affect the overall performance of the LBMM-μEDM process. This work’s primary motivation is to address the research gap in the field of LBMM-μEDM-based micro-drilling, as mentioned above.
2 Materials and methods

This study was carried out experimentally to investigate the effect of various laser parameters on the overall performance of the LBMM-μEDM process. Initially, sub-millimeter holes were drilled using the LBMM method with a programmed diameter of 200μm, which was later fine finished using the μEDM operation. The LBMM drilling task was performed using a desktop fiber laser machine (ytterbium doped) machine (rated maximum power 20 W, actual maximum power was ~16.7 W, measured using Gentec prento laser power meter), as shown in Fig. 1a. The laser that is used in this machine is a pulsed laser with a wavelength of 1060 nm. The focal length of this laser is 200 mm. An X/Y galvanometer scanner (maximum scan angle ±15° and resolution 12 μrad) can control the laser beam to create the various patterns on the workpiece. Figure 1b shows the scanning strategy followed during the LBMM process to make the pilot holes. The line spacing between each scan line was 10 μm, as indicated in Fig. 1b. The whole laser system, including the galvanometer, can be controlled using an integrated graphical user interface (GUI). Three parameters can be controlled in the LBMM system, namely, the laser power, the pulse frequency, and the laser scanning speed, for a feature with fixed geometry.

Following the LBMM drilling operation, the workpiece and the fixture were transferred to the μEDM machine (DT110, Fig. 1c) from Mikrotools Pte. Ltd. The μEDM is a CNC programmable machine that has a positional accuracy of ±1 μm per 100 mm of travel length. The programming resolution of this machine is 0.1 μm. The EDM power supply of this machine is an RC pulse generator. The stray capacitance of the system was measured by monitoring the single pulse discharge energy which was found to be 0.6 nF. The material used for this study was stainless steel (SS304) with a thickness of 0.2 mm. Table 1 describes the laser and μEDM parameters that have been used for this research. It is to note that μEDM parameters were kept constant, whereas the laser parameters were varied in four stages with a full factorial experimental design.

At first, a square array of pilot holes was drilled with different laser parameters as per the experimental design. The time needed to drill each hole by the LBMM process was recorded using a stopwatch (resolution was 1/100th of a second). In the second phase, fine machining was performed on
the μEDM (DT110) machine. Schematically the overall sequential machining process is described in Fig. 2. To carry out the fine machining by μEDM, a 500 μm tungsten tool was used. To maintain the tungsten tool’s positional accuracy above the laser-drilled holes, an on-machine measurement (OMM) system was developed that consists of a variable lens optical microscope equipped with a high-resolution digital camera. As described in Fig. 2, the OMM was mounted adjacent to the μEDM spindle.

The method that was followed to position the tungsten tool above the LBMMed holes accurately is described here. At first, the sample workpiece was firmly attached with the fixture, and arrays of LBMMed holes were machined. Following this, the whole fixture and the workpiece were transferred to the μEDM (DT110) machine, and a reference hole was machined (using the μEDM process) near the arrays of LBMMed holes. The reference hole coordinates were made known to us from the linear scale feedback of the μEDM machine. Next, with the help of the camera (crosshair mark) and linear scale feedback, the deviation of X and Y coordinates for each LBMMed hole from the reference hole was measured and subsequently added to the reference hole’s coordinates.

| Parameter                  | Laser          | μEDM |
|----------------------------|----------------|------|
| Average power (%)          | 15, 40, 65, 90 | -    |
| Measured average power (W) | 6.4, 9.4, 12.5, 15.5 | - |
| Laser spot diameter (μm)   | 40             | -    |
| Laser pulse duration (ns)  | 100            | -    |
| Pulse frequency (kHz)      | 5, 10, 15, 20  | -    |
| Voltage (V)                | -              | 80   |
| Capacitor (nF)             | -              | 1    |
| Stray capacitance (nF)     | -              | 0.6  |
| Laser scanning speed (mm/s)μEDM feed speed (μm/s) | 50, 500, 950, 1400 | 5 |
| Set diameter of the hole for laser operation (μm) | 200 | - |
| Electrode diameter for μEDM (μm) | - | 500 |
| Loop count (Nos)           | 75             | -    |
| μEDM electrode rotational speed (RPM) | - | 500 |
| μEDM electrode material    | -              | Tungsten (W) |

Fig. 2 Schematic illustration of the sequential micromachining process LBMM-μEDM
Thus, the tungsten tool was positioned right on the top of the center of the LBMMed holes for fine machining with acceptable accuracy (theoretically the accuracy is within 2 μm). To evaluate qualitatively the accuracy of the EDM tool’s positioning method over the LBMMed holes, the μEDM operation was carried out on the LBMMed hole partially, and an optical image was captured (Fig. 3). It is quite clear from Fig. 3 that the μEDM tool could be positioned on top of the pilot holes with adequate accuracy using the developed OMM system. Next, the time needed to drill each hole (by μEDM) was recorded from the machine directly without the need of a stopwatch.

The discharge current amplitude and frequency were measured using a current probe (Tektronics: Tek CT1, sensitivity 5mV/mA) as it was attached with an oscilloscope (RIGOL). During the EDM process, a short circuit may occur due to metal to metal contact, which causes no material removal [30]. When short circuit happens (which is detected by the controller of the DT110 machine by monitoring the electrical characteristics of the μEDM process), the machine creates a buzzer sound and causes the tool’s forward motion to be reversed until an open circuit is detected again. The buzzer sound was used to count the total number of short circuits’ occurrence during each μEDM operation. It is to note that the DT110 machine has the capability of detecting a conductive surface as soon as it touches in X, Y, or Z direction. In order to measure the vertical tool wear, the tungsten tool was moved in the negative Z direction to detect a predefined reference surface. Once the surface was detected, the Z coordinate was recorded. This operation was carried out before and after the machining of each hole. Subsequently, the difference between the two Z coordinates was calculated to find the vertical tool wear. For, μEDM operation, each hole the bottom portion of the tungsten tool was flattened using a process called reverse EDM to ensure a similar tool shape for machining all the holes [31].

The characterization of the machined samples was carried out using the scanning electron microscopy (SEM: JSM-IT100 InTouch Scope™), and the characterization was conducted two times, first after the LBMM operation and finally after the μEDM finishing. Once all the SEM images were captured, a third-party image analysis software (ImageJ) [32] was used to measure the holes’ entry and exit areas (both for the LBMMed and the μEDMed holes). The volume of material removed during the LBMM process is a crucial parameter to be measured for this study. This measurement is complicated as LBMMed holes does not have a defined circular shape, and some laser parameters used in this study was unable to penetrate a thru-hole on the workpiece. Figure 4 shows the measurement example using the image analysis software (ImageJ) [32]. Once holes’ areas (entry area: Fig. 4a and c, exit/bottom area: Fig. 4b and d) and slanted height (Fig. 4e) were measured, then the removed volume by the LBMM process each hole was calculated. The hole that was formed by the LBMM process resembles the shape of a cone whose top has been sliced off. If the entry area of the hole is B1 and the exit area of the hole is B2 and the depth of the hole is h, then the formula for volume (V) of material removed by LBMM is given by Eq. (1).

$$V = \frac{h}{3} (B_1 + \sqrt{B_1B_2} + B_2)$$  \hspace{1cm} (1)

It was not possible to measure the depth (h) directly for the holes which were not fully penetrated due to the unavailability of the cross-sectional image of such holes. So, the formula for h in terms of the slanted height was derived as Eq. (2) which was used for the holes like that for Fig. 4e. However, for the case of fully penetrated holes like in Fig. 4a and b, the thickness of the workpiece was taken as h.

$$h = \sqrt{s^2 - \frac{B_1}{\pi} - \frac{B_2}{\pi} + 2 \sqrt{\frac{B_1B_2}{\pi}}}$$  \hspace{1cm} (2)

The abovementioned method of measuring the removed volume during the LBMM process was accurate enough to provide the average trend of material removal by the said process with the variation of laser power and scanning speed.

3 Results and discussions

Figure 5 provides a morphological comparison of the hole quality among the three processes used, namely, LBMM, μEDM, and LBMM-μEDM. LBMM method performs the
best in terms of machining time as it can drill the hole less than 1 min, yet, in regard to the quality of the hole, LBMM performed the worst as it resulted in a thick recast layer and low circularity. On the other hand, the quality of the holes machined by μEDM and LBMM-μEDM sequential process was almost identical. However, the time taken for LBMM-μEDM sequential process to drill the hole was virtually ~2.6 x times lower as compared to pure μEDM method as shown in Fig. 6. The above findings are also in line with the results reported by the previous researchers [29]. Figure 6 also shows that the occurrence of the short circuit during the LBMM-μEDM process was much smaller as compared to the standard μEDM process (~40 x) which indicates that LBMM-μEDM more stable in contrast to pure μEDM.

Additionally, vertical tool wear was also found to be almost ~9 x lower for the case of the sequential micromachining. The reason for the improved machining stability and lower tool wear is because in the

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**Fig. 4** Measurement of LBMMed holes entry, exit, slanted height, and the bottom area for calculating the volume removed by the LBMM process: (a) entry area of a thru-hole, (b) exit area of a thru-hole, (c) entry area of a blind hole, (d) bottom area of the blind hole, and (e) slanted height of the blind hole. Scale bar = 100μm

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**Fig. 5** The morphological comparison of the microholes machined by (a) pure LBMM process, (b) pure μEDM process, and (c) LBMM-μEDM-based sequential process. Laser processing was carried out at 15.5W laser power, 50mm/s scanning speed, and 20kHz pulse frequency. Scale bar = 100μm
LBMM-μEDM method, the total material to be removed from the workpiece is lesser in comparison to the pure μEDM. Moreover, Fig. 7 shows the tilted scanning electron microscopic views of the holes. It can be seen from Fig. 7 that pilot hole machined by the LBMM process contains significant recast layer (similar to Fig. 5) with a non-uniform inner surface (a). The recast layer can be entirely removed, and hole with a uniform inner surface can be created by the subsequent μEDM-based finishing operation Fig. 7b. Further to note that the quality of the LBMM-μEDMed hole (Fig. 7b) is as good as the pure μEDMed hole (Fig. 7c) in terms of the inner surface uniformity and minimized recast layer. In the next sections, we will discuss how various LBMM parameters influence different performance indicators of the LBMM-μEDM-based sequential micromachining. Among the three laser parameters that we varied in this study (pulse frequency, scanning speed, and power), pulse frequency did not show any dominant effect on the performance of the said sequential micromachining process.

3.1 Study of μEDM machining time for laser-μEDM process

As mentioned before, this study was conducted on LBMM-μEDM-based sequential micromachining process where the LBMM was used first followed by the μEDM machining to fine finish the LBMMed holes. The time for the LBMM machining was insignificant as compared to the finishing time by μEDM. Figure 8 demonstrates how the μEDM machining time is varied for the pilot holes drilled with various laser power, scanning time, and pulse frequency. Our study confirms that pulse frequency has no significant effect on the μEDM machining time. We observed that pilot holes machined with higher laser power and slower scanning speed require lesser time to be fine finished by μEDM. However, for the LBMMed holes machined with fast scanning speed, the effect is the opposite.

As the laser pulse frequency was found to have a random effect on the final machining time by μEDM, it was averaged up. Figure 9 shows the effect of laser power and scanning speed on the machining time.
speed (with the frequency effect being averaged) on the final μEDM time to get more quantitative insight into the whole process. It can be inferred from Fig. 9 that if a scanning speed of less than or equal to 200 mm/s is used with any range of laser power (6.4W to 15.5W) for the LBMM operation, then final μEDM operation can be completed within 30 min. Further, for high laser power (≥13 W), even the highest scanning speed can be used for the LBMM machining, yet final finishing procedure by μEDM can be done in less than or equal to 30 min. Figure 10 shows the average discharge frequency and discharge current measured during the μEDMing operation of the LBMMed holes. This figure (Fig. 10a and b) also reinforces the finding that the machinability improves for the LBMMed holes processed with higher laser power and lower scanning speed as both discharge frequency and discharge value increases due to the improvement in the ease of machining [33]. The phenomena observed in Fig. 8 and Fig. 9 can be explained from the study of the LBMMed holes entry, exit area, and removed volume during the LBMM process.

Figure 11 describes the effect of laser power and pulse frequency on the entry area of the initial holes for different laser scanning speed. It can be realized from Fig. 11a–d that holes’ entry area has an increasing trend with the laser power. However, we could not find any significant relation between the entry area and the pulse frequency of the laser. Further, Fig. 12 shows the SEM images of the holes machined at different laser power which also confirms the increasing trend in the entry area (Fig. 12a–d) with the incident laser power. On the other hand, Fig. 13 describes that higher laser scanning speed averagely causes the entry area of the LBMMed holes to be reduced. Negarestani et al. [34] stated that in the LBMM process, the incident energy density is proportional to the laser power and inversely proportional to the scanning speed. In our study, as the incident energy became higher with the increase in the laser power, the entry area of the hole was also expanded.

Similarly, lower energy density due to the faster scanning speed decreased the holes’ entry area. Regarding the exit area of the LBMMed holes, phenomena similar to the entry area was observed, as shown in Fig. 14a–d. However, it can be said that the effect of scanning speed was found to be more dominant on the variation of the exit area as compared to the entry area, which is also visible from the SEM images, as shown in Fig. 15a–d. At a slow scanning speed like 50 mm/s, we had
holes significantly penetrated for the whole range of power. As the scanning speed was equal or more than 500 mm/s, laser power less than or equal to 9.4W could not melt and vaporize the material enough to result in LBMMed holes with substantial exit area. Also, Fig. 16 demonstrates that the volume of material removed during the LBMM process increases with increasing average laser power and decreases with higher scanning speed. The trend of the μEDM machining time observed in Fig. 8 and Fig. 9 is the effect of LBMMed holes’ volume resulting from laser power and scanning speed.

Fig. 10 The average discharge current and discharge frequency variation during the μEDM process as a function average laser power and scanning speed used for the pilot hole machining. (a) variation of the discharge current and (b) variation of the discharge frequency

Fig. 11 The effect of the incident laser power and pulse frequency on the entry area of the pilot holes machined by the LBMM process. (a) The scanning speed was at 50mm/s. (b) The scanning speed was at 500mm/s. (c) The scanning speed was at 950mm/s. (d) The scanning speed was at 1400mm/s. The loop count for all cases was 75. The error bar shows the overall uncertainty
variation. As mentioned, higher incident laser power and lower scanning speed caused significant removal of material during the pilot hole machining by the LBMM process. Therefore, during the μEDM operation, the machine required to remove lesser material that caused in faster processing time (Fig. 8 and Fig. 9).

### 3.2 Study of μEDM machining stability and tool wear for laser-μEDM process

Machining stability for the μEDM process (secondary operation of LBMM-μEDM machining) is denoted by the short circuits' occurrence during the operation. The DT110 μEDM machine is designed in such a way that if there is a detection of the short circuit during the μEDM process, the tool path of the electrode will be reversed to overcome the temporary short circuit condition. The μEDM operation is said to be unstable if too many short circuits are detected in a single machining process. As μEDM is an electrothermal method, it causes the electrode to be worn out also due to the repeated sparks. In this study, we have measured both the short circuit and the vertical tool wear by the method explained in section 2. As described in Fig. 17a–d, it is clear that both tool wear and short circuit during μEDM finishing decrease if higher laser power and slower laser scanning speed are used during the LBMM based rough drilling. This phenomenon can be explained from Fig. 18 which shows that both tool wear and number of short circuits during μEDM is highly correlated (positively) with the μEDM time with the correlation factors 0.92 (Fig. 18a) and 0.99 (Fig. 18b), respectively. This means that higher μEDM time will cause more increased tool wear and short circuit occurrence due to the more extended tool and workpiece interaction. Figure 9 confirms that if higher laser power and slower scanning speed are used for LBMM drilling, then μEDMing time required for fine finishing of the LBMMed holes will be reduced, hence lower tool wear and short circuit occurrence during the operation. If the LBMM process uses the power of 6.4W with scanning speed as high as 1500 mm/s, then the tool wear and short circuit can go up to ~58 μm and ~1045, respectively,

![Image](image_url)
which is almost similar to that of pure μEDM. However, if a high power of 15.5W or above is used with any range of scanning speed, then the tool wear and the number of the short circuit will be around ~10 µm and ~100, respectively, which is substantially reduced than the pure μEDM (Fig. 6). Figure 19 a–b further confirm that not only the total tool wear and total short circuits but also the average rate of tool wear and the average rate of the short circuit also significantly influenced by the laser input parameters that are used for the pilot hole machining. The rate of tool wear and short circuit during the μEDM process can go up to as high as 1µm/min and 20nos/min if high laser scanning speed is used at a low laser incident power during the LBMM process. When low laser power and high scanning speed are used during the LBMM method, then the volumetric size of the LBMMed pilot holes become smaller (Fig. 16). Hence, at the time of μEDM, the tool needs to remove more material from the workpiece, which resulted in more debris formation. As a result, the rate of short circuit and tool wear also increases, whereas for the case of LBMMed holes with more volume of material removed requiring less material to be removed by the μEDM operation, hence we observed more frequent sparking

Fig. 14 The effect of the incident laser power and pulse frequency on the exit area of the pilot holes machined by the LBMM process. (a) The scanning speed was at 50mm/s. (b) The scanning speed was at 500mm/s. (c) The scanning speed was at 950mm/s. (d) The scanning speed was at 1400mm/s. The loop count for all cases was 75. The error bar shows the overall uncertainty.

Fig. 15 The effect of the incident laser scanning speed on the exit area of the pilot holes machined by the LBMM process. (a) 50 mm/s laser scanning speed, (b) 500 mm/s laser scanning speed, (c) 950 mm/s laser scanning speed, and (d) 1400 mm/s laser scanning speed. The loop count was 75, the incident laser power was 6.4W, and the laser pulse frequency was 15 kHz for all the holes. Scale bar = 100µm
and high discharge current (by monitoring the discharge current) during the process. Therefore, the rate of short circuits occurrence and tool wear decreased.

3.3 Study of residual spatter zone for laser-μEDM process

It is expected that during the sequential LBMM-μEDM micromachining, the zone with residual spatter resulted from the LBMM process [35] should be removed entirely. However, we have seen from our study that if high laser power (15.5W) with low scanning speed is used for the pilot hole drilling (using LBMM) with the currently programmed diameter of 200 μm, then μEDM process may not be able to remove the zone with spatter completely. This problem can be solved in two ways: in the first method, the sample plate can be cleaned with isopropyl alcohol (IPA) wipe followed by cleaning in an ultrasonic bath as suggested by Schaeffer et al. [36]. In the second method, the programmed diameter of the LBMM process could be optimized in such a way that finishing operation by μEDM could altogether remove the residual spatter zone from the surface as generated by the LBMM. We experimentally tried several diameters and found out that if 100 μm is used for the LBMM (laser power 6.4W, scanning speed 200 mm/s, pulse frequency 20 kHz), then μEDM could completely remove the residual spatter zone. Figure 20 shows the comparison between the two holes machined with μEDM and LBMM-μEDM process. It is quite clear from the two pictures (Fig. 20) that both the holes are completely clean from any spatter at the surroundings of the holes. It is obvious that by reducing the LBMMed diameter to a half, the performance parameter of the μEDM process is
compromised. However, it is still significantly better than the pure \( \mu \)EDM as described in Fig. 20 which shows that machining time, tool wear, and short circuit occurrence were improved by 95%, 4 x, and 2.5 x, respectively.

The choice between the two processes (IPA wipe and ultrasonic bath or reducing the LBMMed hole size) for complete removal of the residual spatter depends on the user’s preference. If the users go for IPA wipe and ultrasonic bath-based cleaning technique, then they can go for aggressive parameters during the LBMM process, i.e., higher programmed diameter and high laser power. However, if the users do not have the facilities mentioned above, then they need to choose a lower diameter for the LBMM process with lower power and elevated scanning speed.

4 Conclusion

In this study, we have investigated how different laser parameters affect the various performance indicators of the LBMM-\( \mu \)EDM-based sequential micromachining process. We observed that LBMM-\( \mu \)EDM process could help to lower the production time of the microhole fabrication by a margin of ~2.65 x as compared to pure \( \mu \)EDM, yet maintaining the same quality of the machined hole in terms of free of recast layer, circularity, etc. Concerning the machining time, we found that high laser power and slow scanning speed to produce the pilot holes (as compared to low laser power and fast scanning speed) help to lower the machining time by the \( \mu \)EDM process, up to 250%. We also observed that the tool...
wear and short circuit occurrence during the μEDM process were significantly affected by the size of the LBMMed holes machined by various LBMM parameters. High tool wear rate and short circuit rate were observed (~1 μm/min and ~200nsec/min, respectively) during the μEDM operation if low laser power and high scanning speed were used for the LBMMed holes. Finally, we observed that the residual spatter zone resulted from the LBMM process could be entirely removed by the μEDM process if the programmed diameter for the LBMM process was halved. As a result, the LBMM-μEDM performance was compromised in terms of machining time, tool wear, and short circuit occurrence; however, they were yet considerably better than pure μEDM process.

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Declarations

Ethics approval This paper does not require any ethical approval as the study does not involve human participants or animals.

Consen to participate Not applicable as this work does not involve human subjects.

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References

1. Chavoshi SZ, Luo X (2015) Hybrid micro-machining processes: a review. Precis Eng 41:1–23. https://doi.org/10.1016/j.precisioneng.2015.03.001
2. Rahman M, Asad ABMA, Masaki T, Saleh T, Wong YS, Kumar AS (2010) A multiprocess machine tool for compound micromachining. Int J Mach Tools Manuf 50:344–356
3. Liu Y, Zhu D, Zeng Y, Yu H (2011) Development of microelectrodes for electrochemical micromachining. Int J Adv Manuf Technol 55:195–203. https://doi.org/10.1007/s00170-010-3035-2
4. Mishra S, Yadava V (2015) Laser beam micromachining (LBMM) - A review. Opt Lasers Eng 73:89–122. https://doi.org/10.1016/j.optlaseng.2015.03.017
5. Ghosal A, Manna A, Lall AK (2014) Modelling of ytterbium fiber laser parameters during micro machining of Al-15 wt%Al2O3-MMC. Procedia Eng 90:704–709. https://doi.org/10.1016/j.proeng.2014.11.799
6. Ancona A, Döring S, Jauregui C, Röser F, Limpert J, Nolte S, Tünnermann A (2009) Femtosecond and picosecond laser drilling of metals at high repetition rates and average powers. Opt Lett 34:3304–3306. https://doi.org/10.1364/ol.34.003304
7. Gruner A, Schille J, Loescher U (2016) Experimental study on micro hole drilling using ultrashort pulse laser radiation. Phys Procedia 83:157–166. https://doi.org/10.1016/j.phpro.2016.08.030
8. Barthels T, Reininghaus M, Westergeling H (2019) High-precision ultrashort pulsed laser drilling of micro and nano holes using multibeam processing. In: Dudley A, Laskin A V. (eds) Laser Beam Shaping XIX. SPIE, p 19
9. Casalino G, Losacco AM, Arnesano A, Facchin F, Pierangeli M, Bonserio C (2017) Statistical analysis and modelling of an Yb:KGW femtosecond laser micro-drilling process. Procedia CIRP 62:275–280. https://doi.org/10.1016/j.procir.2016.06.111
10. Ultrafast lasers offer great promise as a unique manufacturing tool | Industrial Laser Solutions. https://www.industrial-lasers.com/home/article/16490420/ultrafast-lasers-offer-great-promise-as-a-unique-manufacturing-tool. Accessed 19 Jan 2021
11. Rajurkar KP, Sundaram MM, Malshpe AP (2013) Review of electrochemical and electrodischarge machining. Procedia CIRP 6:13–26. https://doi.org/10.1016/j.procir.2013.03.002
