

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 (μ EDM) based sequential micromachining technique, LBMM- μ EDM has drawn significant research attention to utilizing the advantages of both methods, i.e. LBMM and μ EDM. In this process, a pilot hole is machined by the LBMM and subsequently finishing operation of the hole is carried out by the μ EDM. 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 μ EDM in this case. The scope of the work is limited to 1-D machining, i.e. drilling micro holes. It was found that laser input parameters mainly scanning speed and power influenced the output performance of μ EDM 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 μ EDM machining time. On the contrary, if the higher laser power is used with even the highest scanning speed for the pilot hole drilling, then μ EDM processing time was faster than the previous case. Similarly, μ EDM time was also quicker for LBMMed pilot holes machined at low laser power and slow scanning speed. Our study confirms that LBMM- μ EDM 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 μ EDM process without compromising the quality of the holes.

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-micrometre 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 and 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 form inaccuracy on the machined feature, i.e. laser micromachining causes the structures to be tapered [5]. The use of ultra-short 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 kHz 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 the circularity of the holes were somewhat inadequate. Barthels et al. [8] also carried out laser drilling of 10mm 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 (μ EDM), electrochemical micromachining (EMM), and micro-milling are few examples of tool-based micromachining process. Micro electro-discharge machining (μ EDM) is a well-established technology used in the field of microfabrication because of its ability to create features in micrometres domain with high tolerance and excellent structural integrity and quality [11]. It is to note that μ EDM is essentially an electrothermal process that utilizes repeated sparks to machine conductive materials such as; metals, metallic alloys, semiconductor etc. with whatsoever hardness [12] [13] [14]. The μ EDM process is free from chatter effect, mechanical stress, and vibration-related problems due to its inherent noncontact material removal mechanism [15]. Besides, μ EDMed surface is almost free from HAZ as compared to the LBMMed ones.

Nonetheless, μ EDM 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 limits the resolution of the features fabricated by μ EDM.

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 μ EDM [20]. Electrical discharge abrasive grinding (EDAG) is another EDM based hybrid machining that combines conventional grinding and EDM [20]. Vibration assisted μ EDM 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 include Laser-assisted turning [24], Laser-assisted milling [25], Laser-assisted waterjet machining [26].

Laser- μ EDM based sequential micromachining has also been reported by researchers [27] [28] [29]. Li et al. [27] proposed LBMM-mEDM 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 ± 20 mm. Kim et al. [28] also investigated micromachining of holes and microstructures using nanosecond pulsed laser and mEDM. The machining time reduction was more than 50% for both micro-drilling and micro-milling operations [28]. Al-Ahmari et al. [29] investigated LBMM-mEDM based micro-drilling for Ni-Ti-based shape memory alloy (SMA), which helped improve the hole quality to pure LBMMed holes. A challenge for LBMM-mEDM sequential machining is the alignment of the mEDM tool on the LBMMed pilot hole, which is not adequately described in the previous research [27] [28] [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- μ EDM process. This work's primary motivation is to address the research gap in the field of LBMM-mEDM 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- μ EDM process. Initially, sub-millimetre holes were drilled using the LBMM method with a programmed diameter of 200mm, which was later fine-finished using the μ EDM operation. The LBMM drilling task was performed using a desktop fibre 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. 1 (a). 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 $\pm 15^\circ$, and resolution 12 μ rad) can control the laser beam to create the various patterns on the workpiece. Figure 1(b) shows the scanning strategy followed during the LBMM process to make the pilot holes. The line spacing between each scan line was 10 mm, as indicated in Fig. 1(b). 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 μ EDM machine (DT110, Fig. 1 (c))

from Mikrotools Pte. Ltd. The μ EDM is a CNC programmable machine that has a positional accuracy of $\pm 1 \mu\text{m}$ per 100 mm of travel length. The programming resolution of this machine is $0.1 \mu\text{m}$. 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 μ EDM parameters that have been used for this research. It is to note that μ EDM parameters were kept constant whereas the laser parameters were varied in four stages with a full factorial experimental design.

Table 1
Various parameters for laser and μ EDM

<i>Parameter</i>	<i>Laser</i>	μ <i>EDM</i>
Average Power (%)	15,40,65,90	-
Measured Average Power (W)	6.4,9.4,12.5,15.5	
Laser spot diameter (mm)	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)/ μ EDM feed speed ($\mu\text{m/s}$)	50, 500, 950,1400	5
Set diameter of the hole for Laser operation (μm)	200	-
Electrode diameter for μ EDM (μm)	-	500
Loop count (Nos)	75	-
μ EDM electrode rotational speed (RPM)	-	500
μ EDM electrode material	-	Tungsten (W)

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 μ EDM (DT110) machine. Schematically the overall sequential machining process is described in Fig. 2. To carry out the fine machining by μ EDM, 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 μ EDM 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 μ EDM (DT110) machine, and a reference hole was machined (using the μ EDM process) near the arrays of LBMMed holes. The reference hole coordinates were made known to us from the linear scale feedback of the μ EDM 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. Thus, the tungsten tool was positioned right on the top of the centre of the LBMMed holes for fine machining with acceptable accuracy (theoretically the accuracy is within 2 μ m). To evaluate qualitatively the accuracy of the EDM tool's positioning method over the LBMMed holes, the mEDM 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 mEDM 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 mEDM) was recorded from the machine directly without the need of a stopwatch.

The discharge current amplitude and frequency was 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 mEDM 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 mEDM operation. It is to note that the DT110 machine has the capability of detecting a conductive surface as soon as it touches it 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, μ EDM 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 ScopeTM), and the characterization was conducted two times, first after the LBMM operation and finally after the μ EDM 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 μ EDMed 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. 4 (a) and Fig. 4 (c), exit/bottom area: Fig. 4(b) and Fig. 4 (d)) and slanted height (Fig. 4 (e)) 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 B_1 and the exit area of the hole is B_2 , and the depth of the hole is h , then the formula for volume(V) of material removed by LBMM is given by Eq. (1).

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

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 equation (2) which was used for the holes like that for Fig. 4(e). However, for the case of fully penetrated holes like Fig. 4 (a) and Fig. 4 (b) the thickness of the workpiece was taken as h .

$$h = \sqrt{s^2 - \frac{B_1}{\pi} - \frac{B_2}{\pi} + 2 \frac{\sqrt{B_1 B_2}}{\pi}} \quad (2)$$

The above-mentioned 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, μ EDM and LBMM- μ EDM. LBMM method performs the best in terms of machining time as it can drill the hole less than one minute, yet, in regards 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 μ EDM and LBMM- μ EDM sequential process was almost identical. However, the time taken for LBMM- μ EDM sequential process to drill the hole was virtually $\sim 2.6 \times$ times lower as compared to pure μ EDM 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- μ EDM process was much smaller as compared to the standard μ EDM process ($\sim 40 \times$) which indicates that LBMM- μ EDM more stable in contrast to pure μ EDM.

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 LBMM- μ EDM method, the total material to be removed from the workpiece is lesser in comparison to the pure μ EDM. 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 μ EDM based finishing operation Fig. 7(b). Further to note that the quality of the LBMM- μ EDMed hole Fig. 7(b) is as good as the pure μ EDMed hole Fig. 7(c) 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- μ EDM 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 μ EDM machining time for laser- μ EDM process

As mentioned before, this study was conducted on LBMM- μ EDM based sequential micromachining process where the LBMM was used first followed by the μ EDM machining to fine finish the LBMMed holes. The time for the LBMM machining was insignificant as compared to the finishing time by μ EDM. Figure 8 demonstrates how the μ EDM 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 μ EDM machining time. We observed that pilot holes machined with higher laser power and slower scanning speed requires lesser time to be fine finished by mEDM. 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 mEDM, it was averaged up. Figure 9 shows the effect of laser power and scanning speed (with the frequency effect being averaged) on the final mEDM 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 mEDM operation can be completed within 30 mins. Further, for high laser power (≥ 13 W) even the highest scanning speed can be used for the LBMM machining yet final finishing procedure by mEDM can be done in less than or equal to 30 mins. Figure 10 shows the average discharge frequency and discharge current measured during the mEDMing operation of the LBMMed holes. This figure (Fig. 10 (a) and Fig. 10 (b)) also reinforces the finding 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. 11 (a-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. 12(a-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. 14 (a-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. 15 (a-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 μ EDM machining time observed in Fig. 8 and Fig. 9 is the effect of LBMMed holes' volume resulting from laser power and scanning speed 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 μ EDM operation, the machine required to remove lesser material that caused in faster processing time (Fig. 8 and Fig. 9).

3.2 Study of μ EDM Machining Stability and Tool Wear for laser- μ EDM process

Machining stability for the μ EDM process (secondary operation of LBMM- μ EDM machining) is denoted by the short circuits' occurrence during the operation. The DT110 μ EDM machine is designed in such a way that if there is a detection of the short circuit during the mEDM process, the tool path of the electrode will be reversed to overcome the temporary short circuit condition. The mEDM operation is said to be unstable if too many short circuits are detected in a single machining process. As μ EDM 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 two. As described in Fig. 17 (a-d), it is clear that both tool wear and short circuit during mEDM 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 mEDM is highly correlated (positively) with the mEDM time with the correlation factors 0.92 Fig. 18(a) and 0.99 Fig. 18(b) respectively. This means higher mEDM 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 mEDMing 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 \sim 58 mm and \sim 1045 respectively which is almost similar to that of pure mEDM. 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 \sim 10 mm and \sim 100 respectively which is substantially reduced than the pure mEDM (Fig. 6). Figure 19 (a-b) further confirms that not only the total tool wear and total short circuits but 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 mEDM process can go up to as high as 1mm/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 mEDM, 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 requires less material to be removed by the mEDM operation hence we observed more frequent sparking 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- μ EDM process

It is expected that during the sequential LBMM- mEDM 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 mm then mEDM 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 mEDM 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 mm is used for the LBMM (laser power 6.4W, scanning speed 200 mm/s, pulse frequency 20 kHz) then mEDM could completely remove the residual spatter zone. Figure 20 shows the comparison between the two holes machined with mEDM and LBMM-mEDM 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 mEDM process is compromised. However, it is still significantly better than the pure mEDM 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-mEDM based sequential micromachining process. We observed that LBMM-mEDM process could help to lower the production time of the micro-hole fabrication by a margin of ~ 2.65 x as compared to pure mEDM, 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 mEDM process, up to 250%. We also observed that the tool wear and short circuit occurrence during the mEDM process were significantly affected by the size of the LBMMed holes machined by various LBMM parameter. High tool wear rate and short circuit rate were observed ($\sim 1\text{mm/min}$ and $\sim 20\text{nos/min}$ respectively) during the mEDM 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 mEDM process if the programmed diameter for the LBMM process was halved. As a result, the LBMM-mEDM performance was compromised in terms of machining time, tool wear and short circuit occurrence; however, they were yet considerably better than pure mEDM process.

Declarations

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

Consent to Participate: Not applicable as this work does not involve human subjects.

Consent to Publish: Not applicable as this work does not involve human subjects.

Authors' Contributions: Mir Akmam Noor Rashid and Wazed Ibne Noor are the graduate students involved in this project who actively carried out the experiments, characterizations, compilation and analysis of the data. Mir Akmam Noor Rashid mostly contributed to drafting the article. Tanveer Saleh is the principal investigator of the projects who conceptualized whole research problems. He is the main supervisor of the above students and guided them during experimentation and data analysis. Mohamed Sultan Mohamed Ali is one of the research collaborators who provided crucial technical input on the manuscript.

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Figures

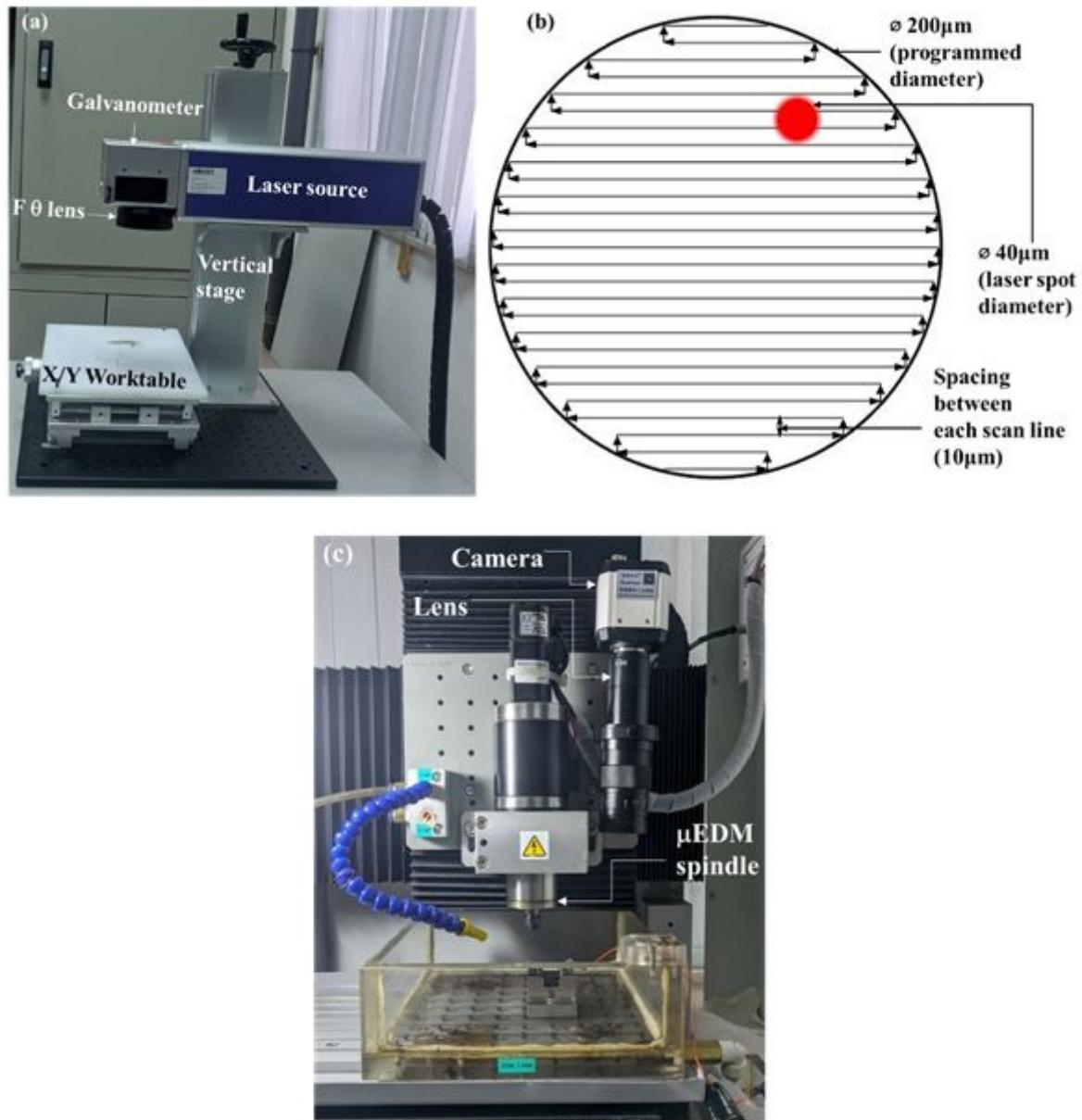


Figure 1

(a) Fiber laser machining setup (b) Scanning strategy for the LBMM process and (c) uEDM setup.

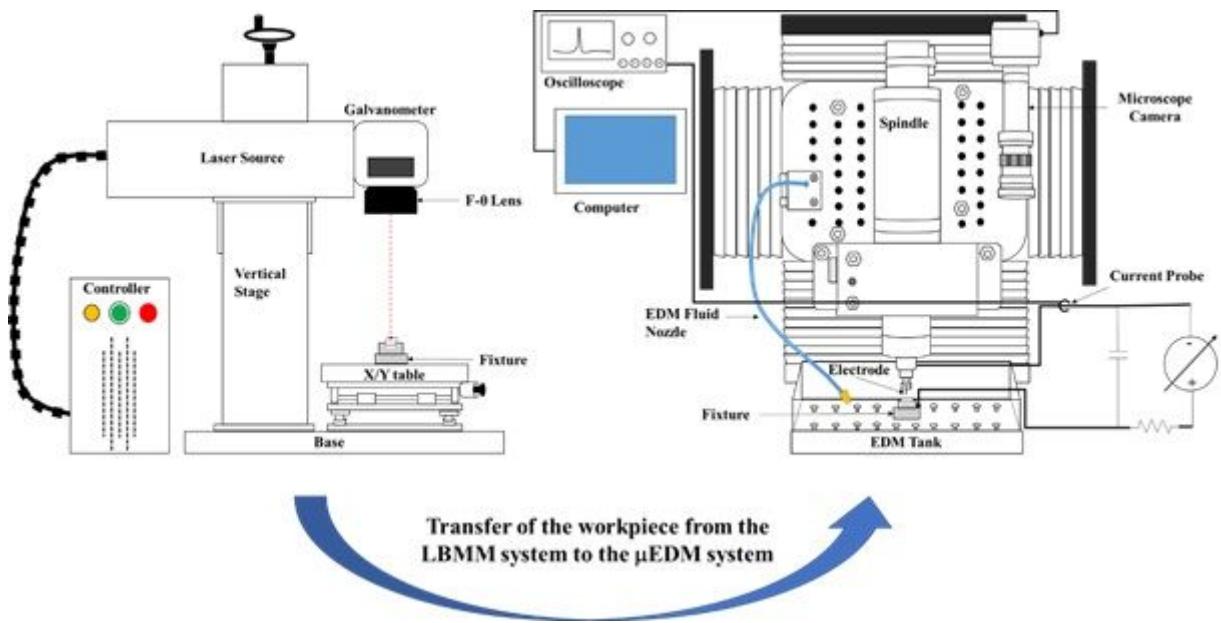


Figure 2

Schematic illustration of the sequential micromachining process LBMM-uEDM.

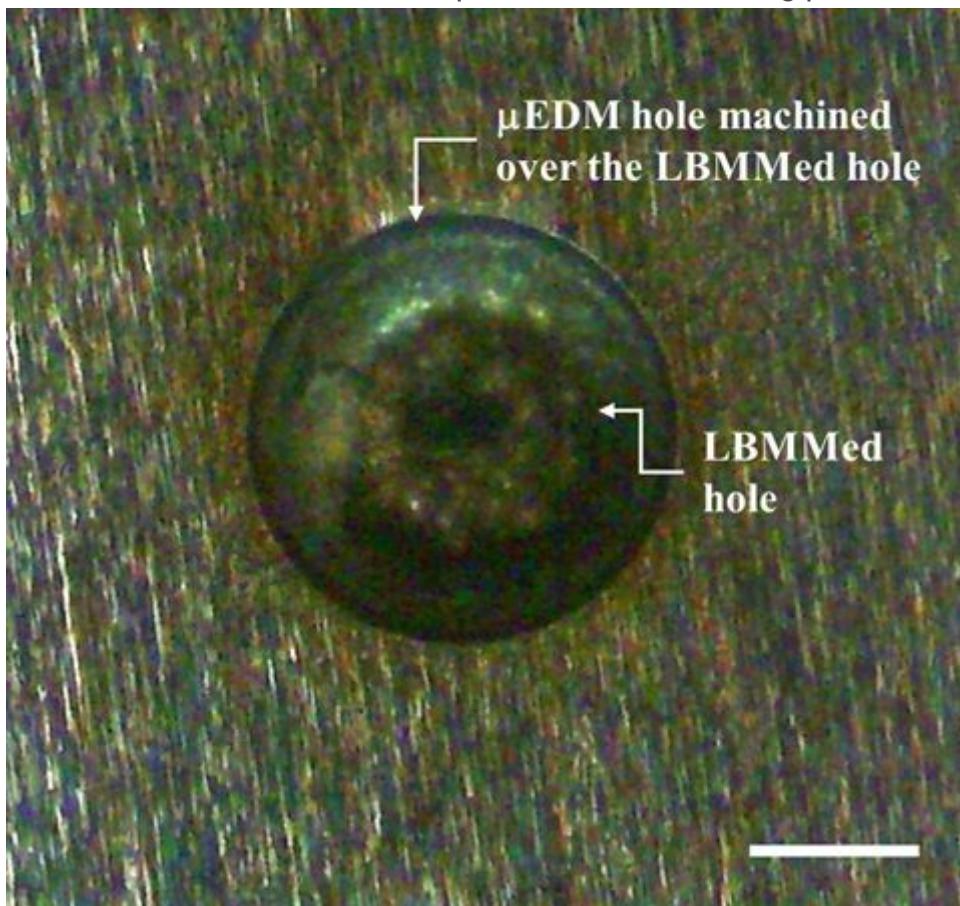


Figure 3

Demonstrates the effectiveness of the proposed centering method of the uEDM tool on the pre-machined LBMMed hole. Scale bar = 200um

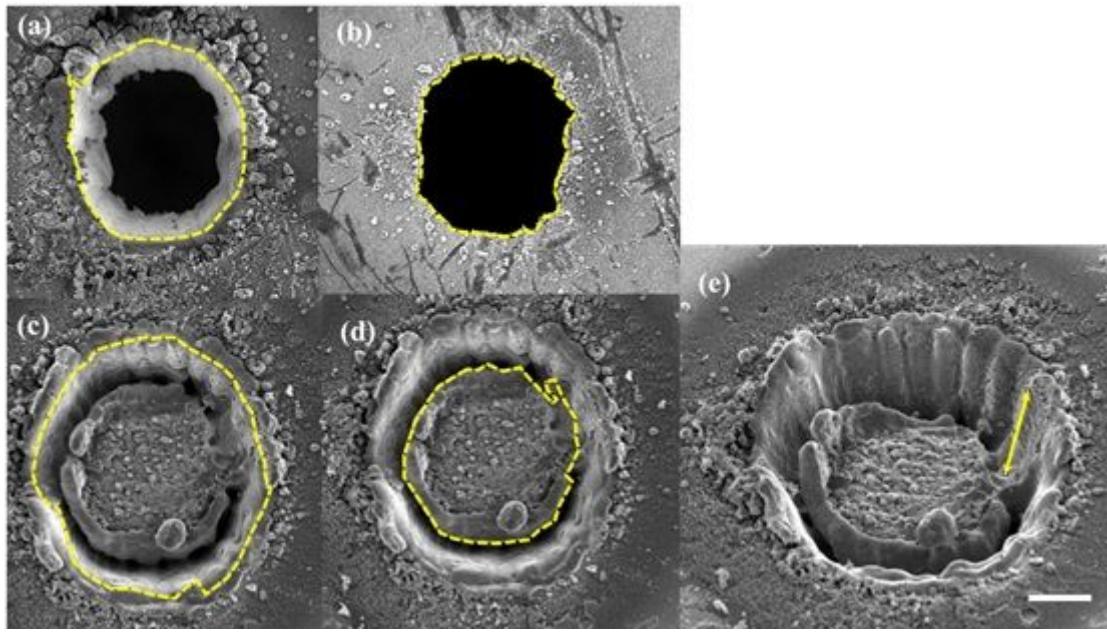


Figure 4

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 = 100um.

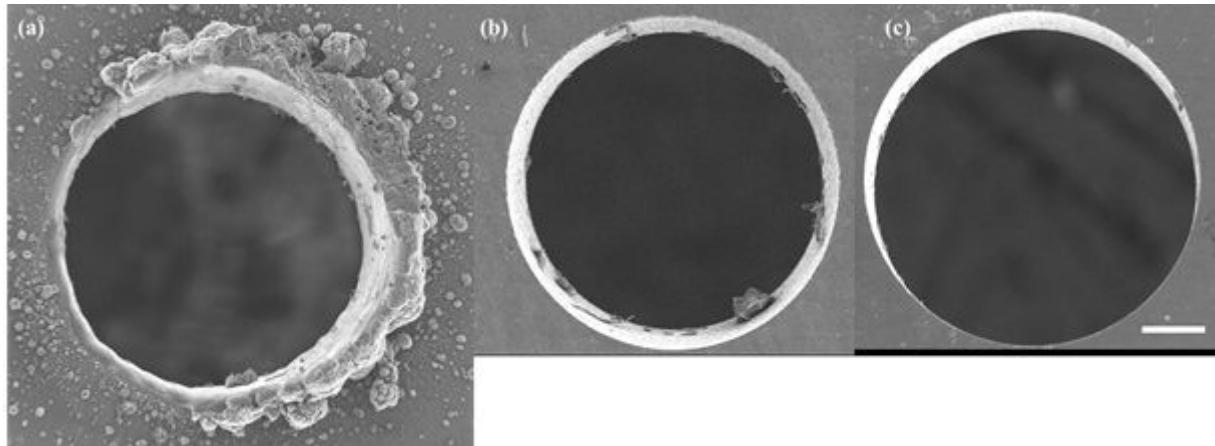


Figure 5

The morphological comparison of the micro holes machined by (a) pure LBMM process, (b) pure uEDM process and (c) LBMM-uEDM based sequential process. Laser processing was carried out at 15.5W laser power, 50mm/s scanning speed and 20kHz pulse frequency. Scale bar = 100um.

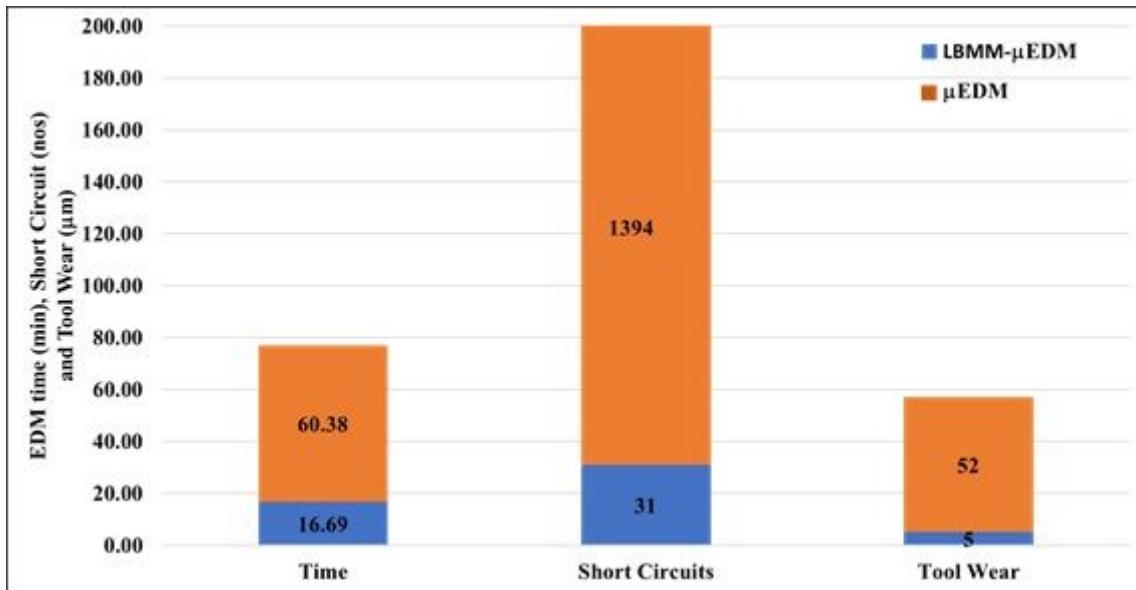


Figure 6

Comparison of machining time, nos of short circuits and tool wear between LBMM-uEDM and pure uEDM.

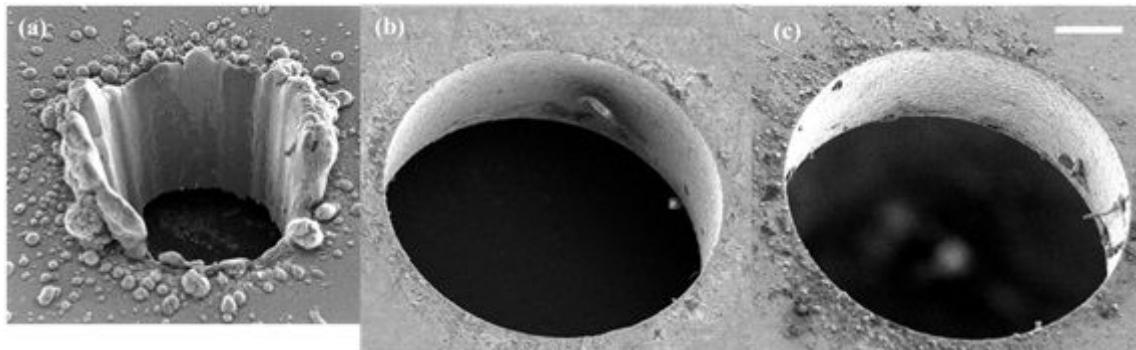


Figure 7

Morphological study of the micro holes (a) initially machined by the LBMM process (b) fine finished by the uEDM process and (c) fully machined by the uEDM process. Scale bar = 100um.

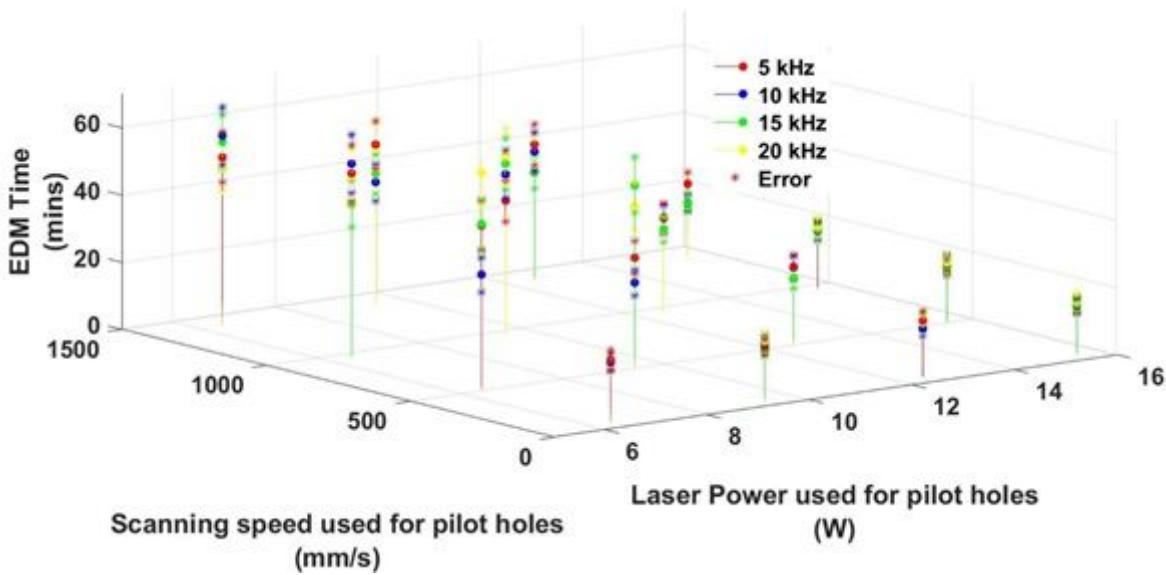


Figure 8

The effect of the incident laser power, scanning speed and pulse frequency (used for the pilot hole machining) on the uEDM processing time for the final finishing of the pilot holes. The error bar represents the machining uncertainty.

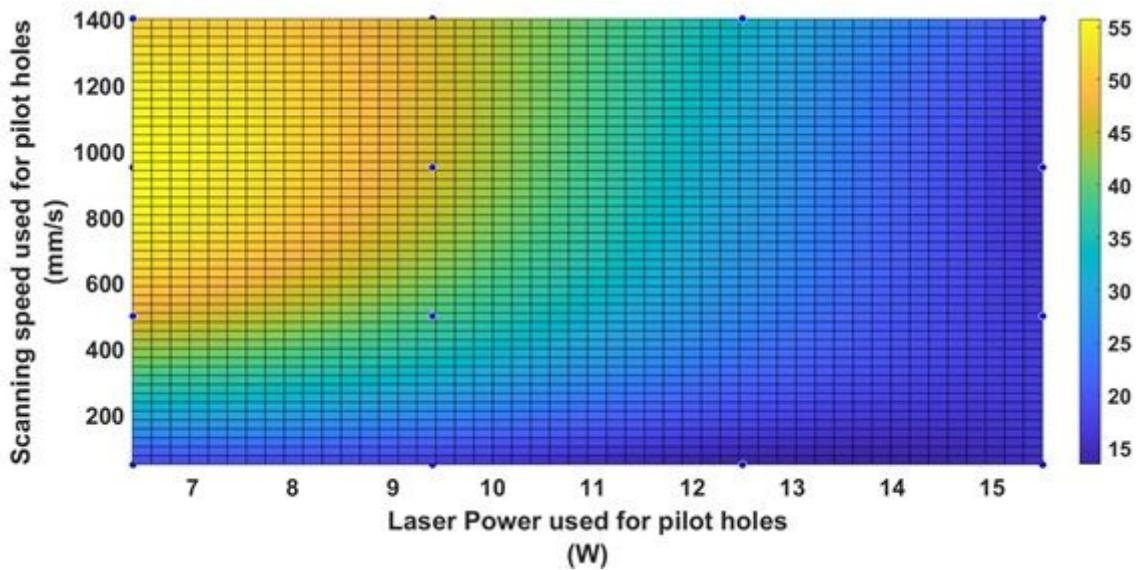


Figure 9

The zone of faster and slower uEDM machining time as a function of laser incident power and laser scanning speed (used for pilot hole drilling using the LBMM process).

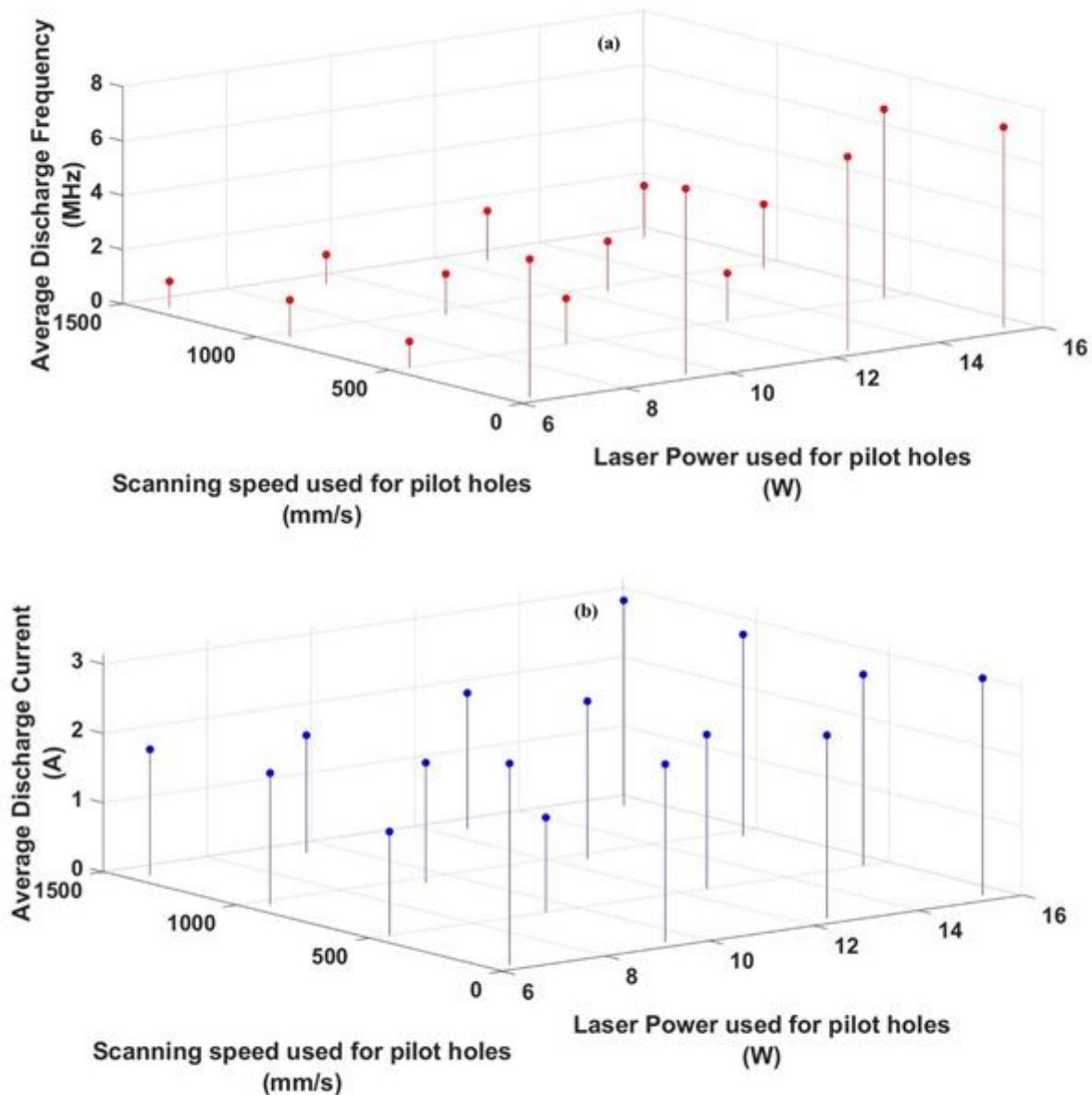


Figure 10

The average discharge current and discharge frequency variation during the uEDM 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.

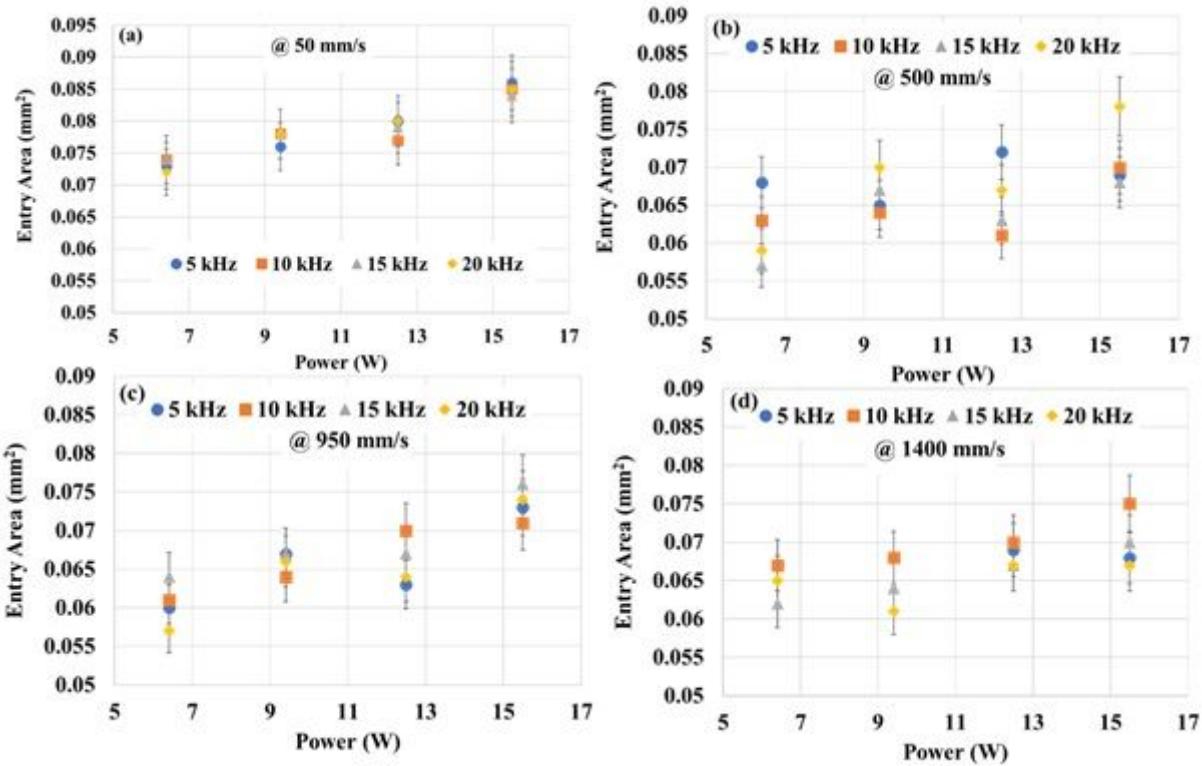


Figure 11

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.

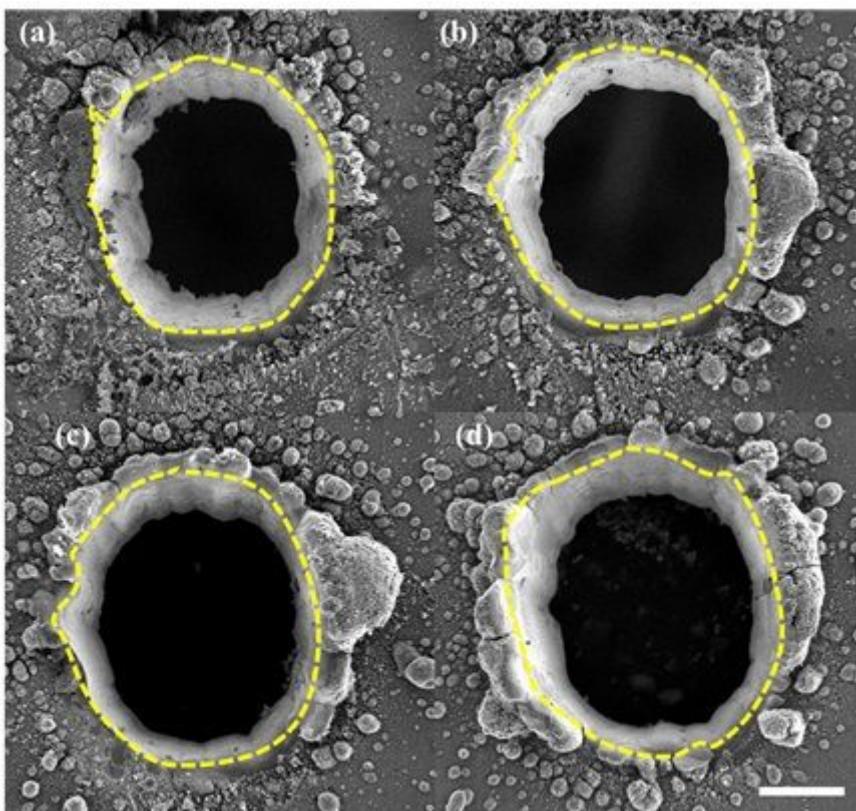


Figure 12

The SEM images of the entry area of the LBMMed holes machined by different incident laser power. (a) 6.4W laser power, (b) 9.4W laser power (c) 12.5W laser power and (d) 15.5W laser power. The loop count was 75, the scanning speed was 50mm/s, and the laser pulse frequency was 5 kHz for all the holes. Scale bar = 100um. Black edge marker is used to highlight the entry area.

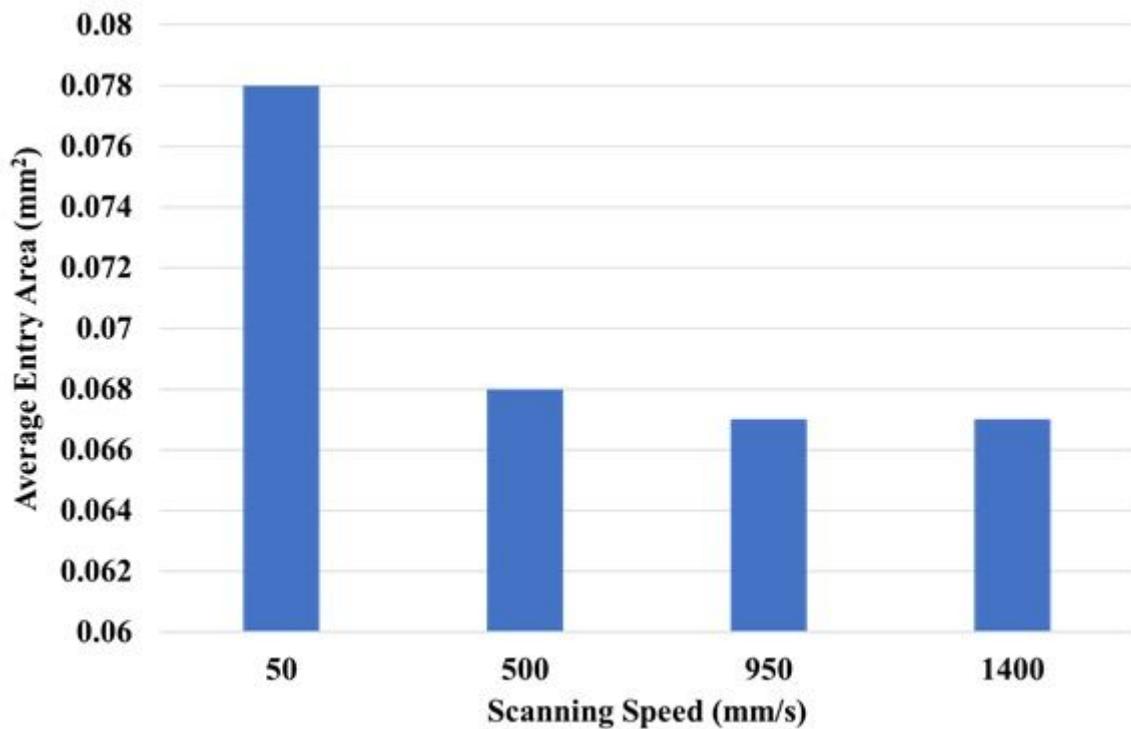


Figure 13

The average effect of the laser scanning speed on the entry area of the pilot holes machined by the LBMM process. All the data for each scanning speed has been averaged up to plot this graph.

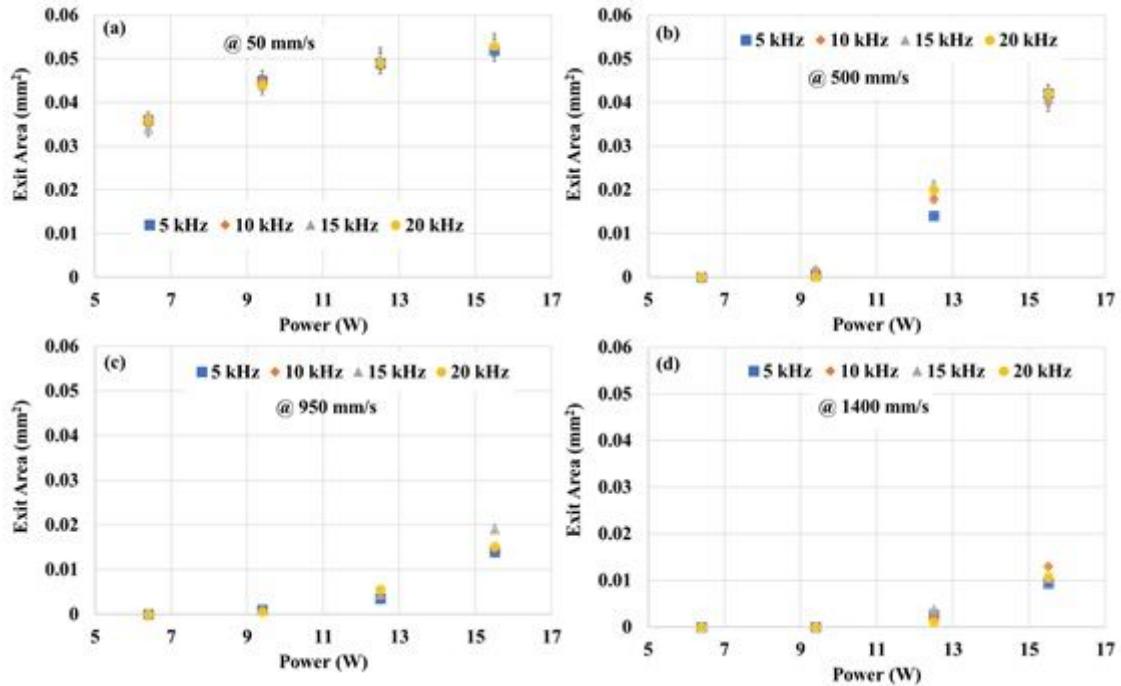


Figure 14

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.

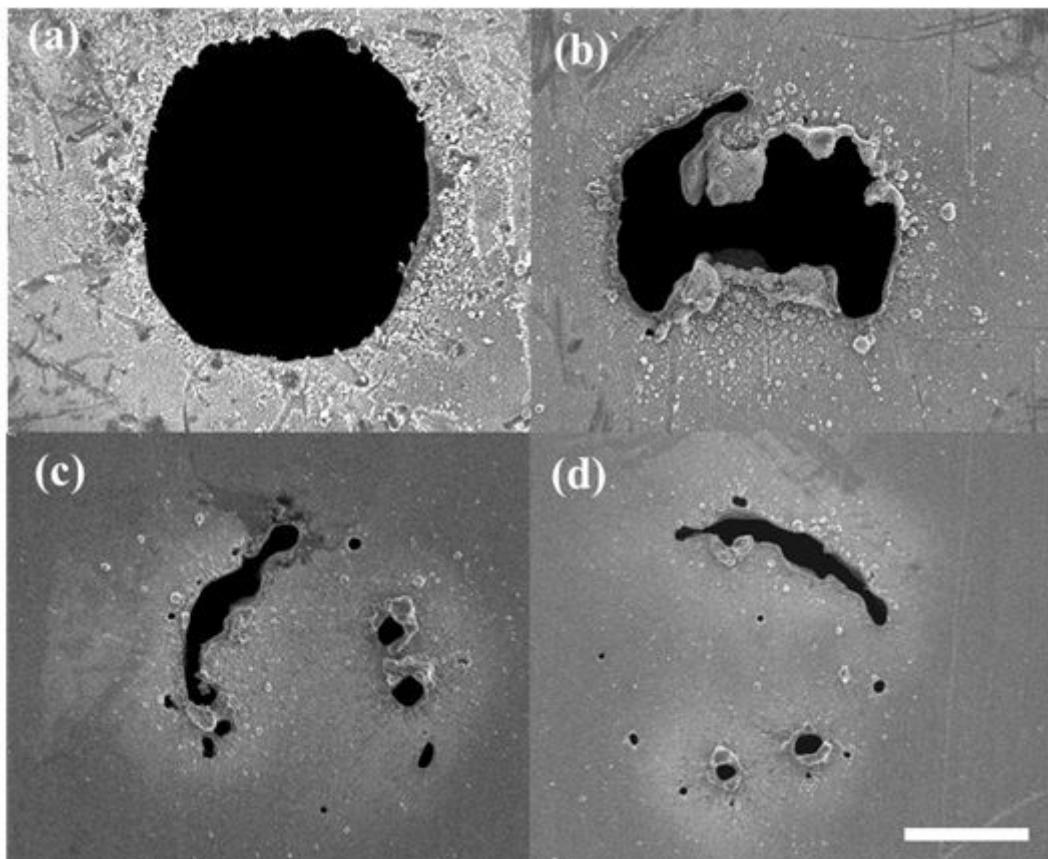


Figure 15

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,(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 = 100um.

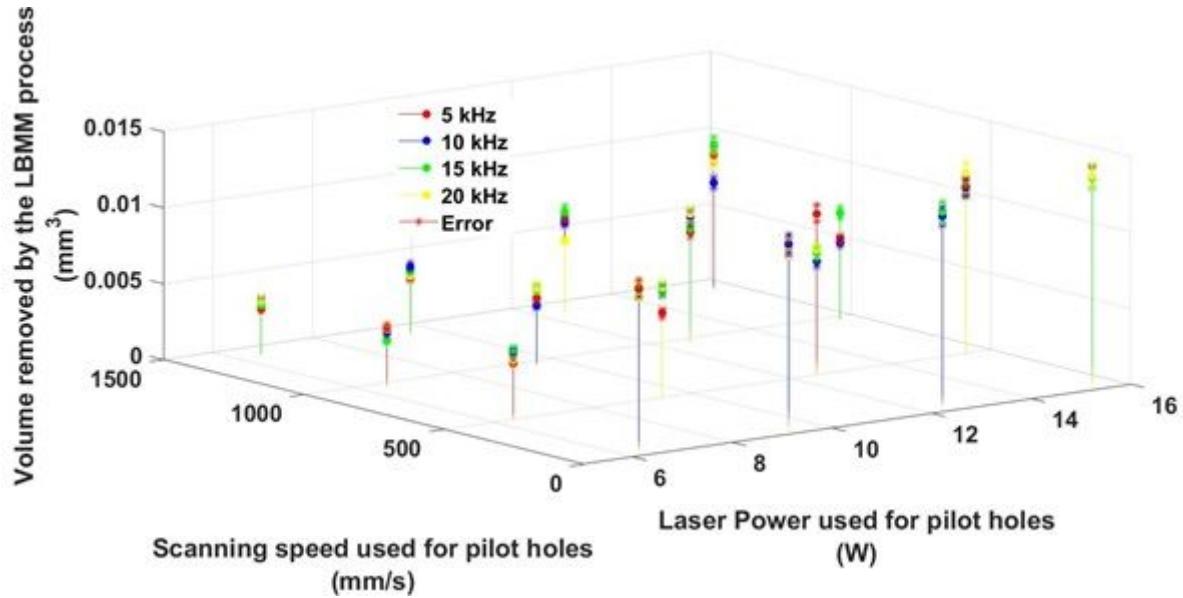


Figure 16

The volume of material removed by the LBMM process as a function of average laser power and scanning speed.

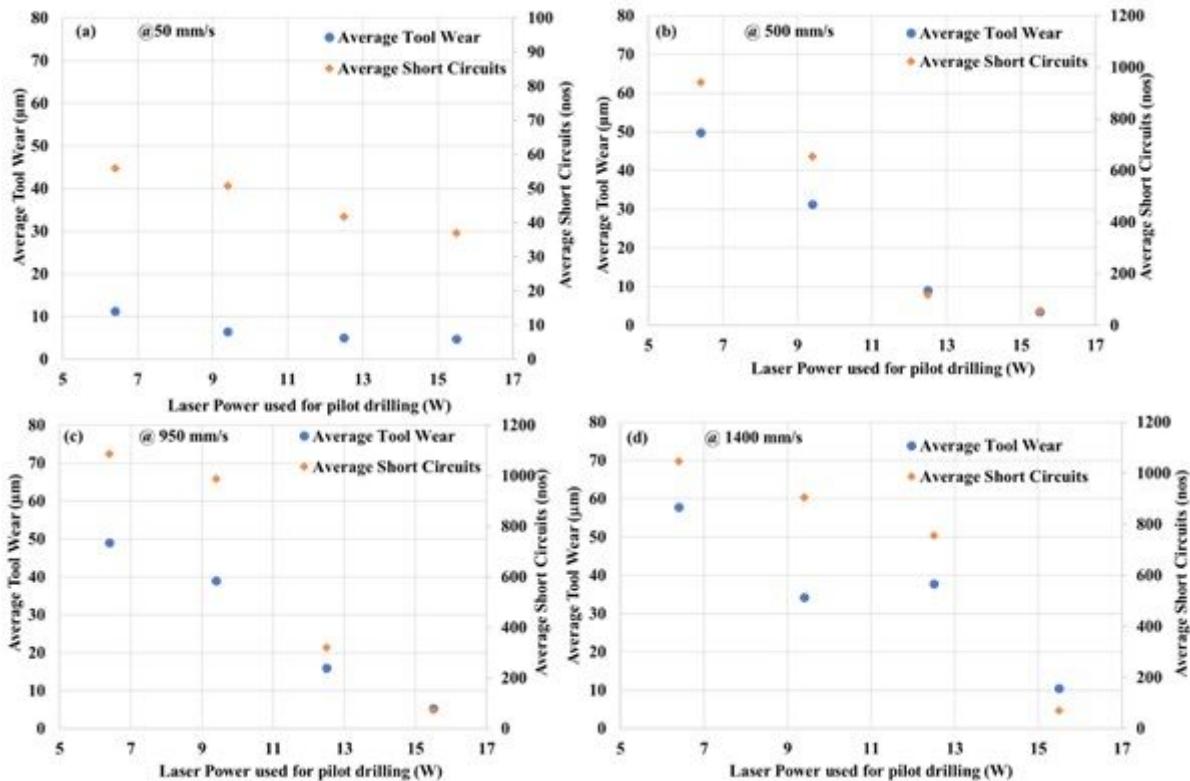


Figure 17

The variation of average tool wear and number of the short circuit during the uEDM process as a function the incident laser power used for the pilot holes drilling. (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 was 75 for all the cases.

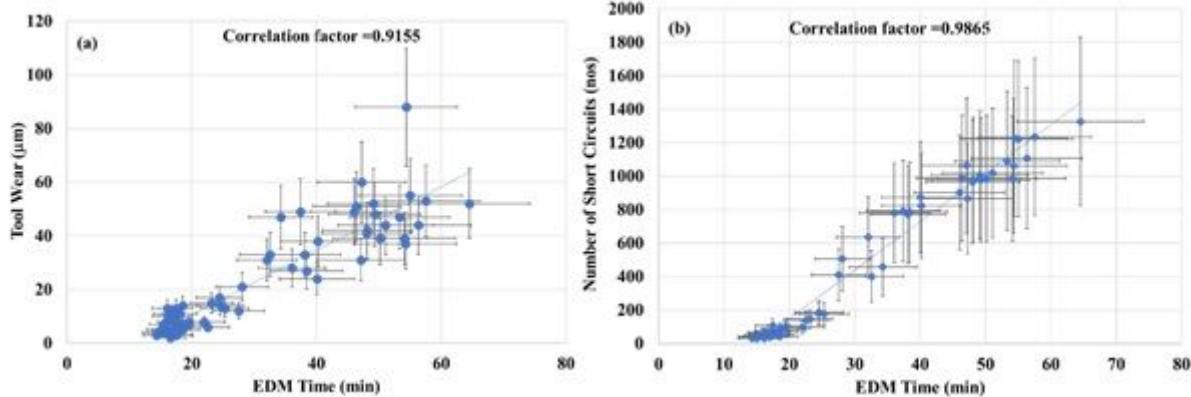


Figure 18

The correlation between tool wear and short circuits vs uEDM time. (a) Tool wear vs uEDM time. (b) Short circuits vs uEDM time. Error bar shows the experimental variation.

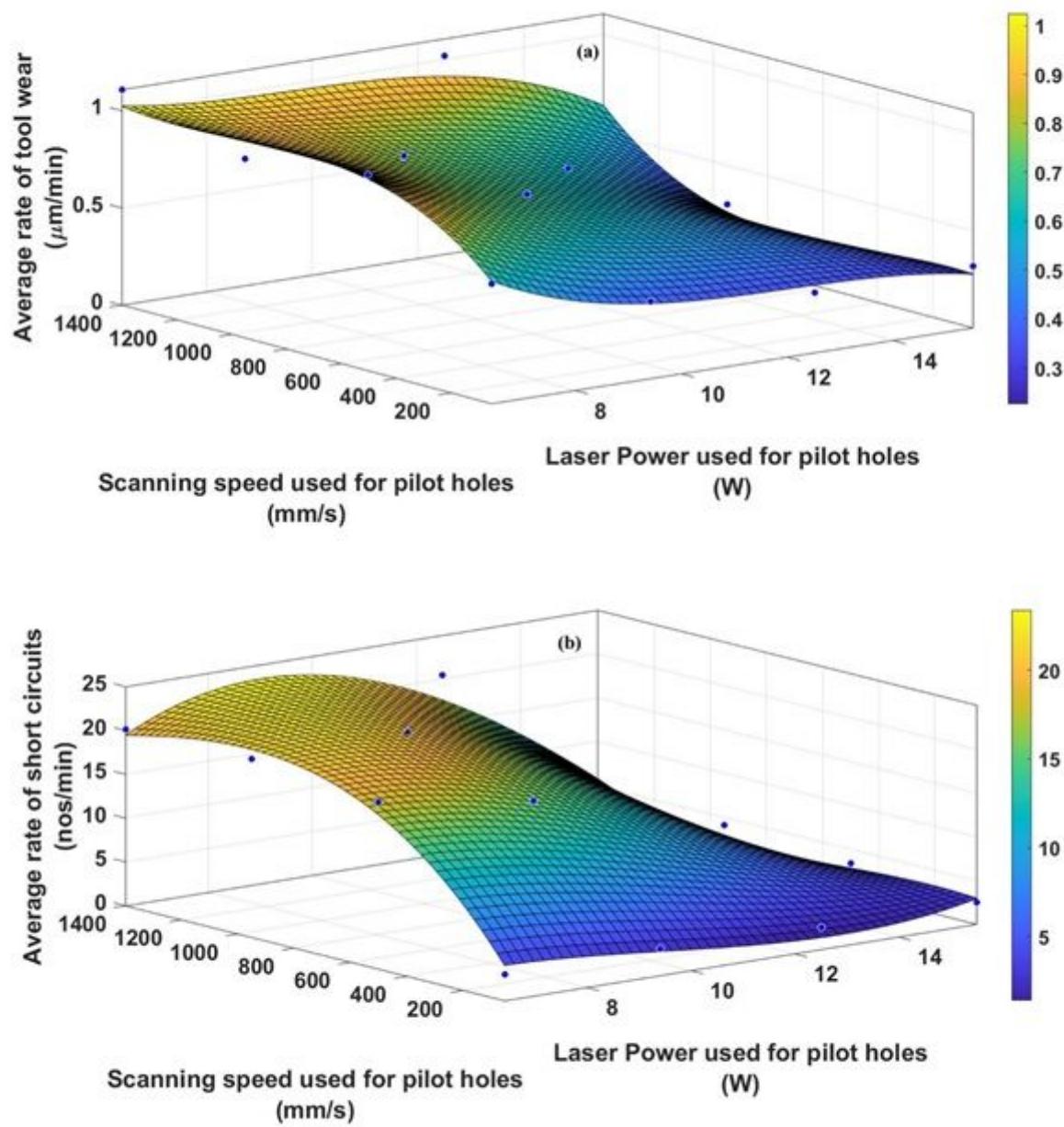
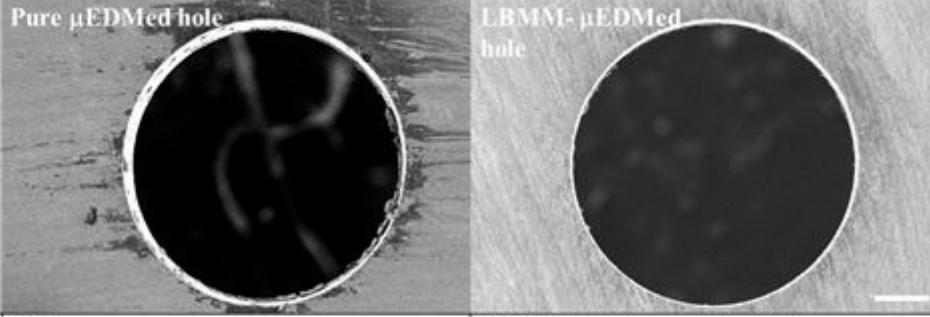


Figure 19

The average tool wear rate and the short circuit occurrence rate as a function of laser incident power and laser scanning speed (used for pilot hole drilling using the LBMM process) (a) Rate of tool wear and (b) rate of short circuit occurrence.



Pure μEDMed hole	LBMM-μEDMed hole
μEDM time	61.26
Tool wear (μm)	73
Short Circuits Count (nos)	1327
	31.35 (improved by more than 95%)
	14 (improved by more than 400%)
	367 (improved by more than 250%)

Figure 20

Comparison between pure uEDMed hole and LBMM-uEDMed holes. Both holes confirm that there is no residual spatter zone present on the surrounding of the hole. Scale bar = 100um