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A machine learning-based classification model to identify the effectiveness of vibration for μEDM

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Abstract Micro electro-discharge machining (μEDM) uses electro-thermal energy from repetitive sparks generated between the tool and workpiece to remove material from the latter. However, one of the bottlenecks of μEDM is the phenomenon of short circuits due to the physical contact between the tool and debris (formed during the erosion of the workpiece). Adequate flushing of the debris can be achieved by applying low amplitude high-frequency vibration to the workpiece. This study, however, shows that the application of vibration does not yield beneficial results for the μEDM for all the parametric conditions. This research used an off-the-shelf piezo vibrator as the high-frequency, low amplitude vibration source to the workpiece during the μEDM process. The experiments were conducted with and without vibration with the variation of applied discharge energy and μEDM speed. The samples were characterized using scanning electron microscopes to gather various data related to μEDM outputs. The results of this study revealed that vibration-assisted μEDM becomes less effective as the discharge energy is increased (primarily by increasing the capacitor value of the RC pulse generator). Similarly, the reduction of the occurrence of the short circuit was profound when the low discharge energy level with low voltage and low capacitor setting of the RC Pulse generator was used. The overall scale of the overcut with various discharge energy and μEDM speed varied from 15.5 μm to 42 μm for the conventional μEDM process. However, the scale above slightly reduced to 14.5 μm to 39 μm using an ultrasonic vibration device. Also, the taperness of the machined hole was slightly reduced by applying the vibration device during the μEDM operation (overall average of ~7%).

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Nomenclature

EDM	Electro-Discharge Machining	MRR	Material Removal Rate
μEDM	Micro Electro-Discharge Machining	TW	Tool Wear

1. Introduction

As a low-cost alternative to conventional machining, micro electro-discharge machining (μEDM) offers unique benefits for cutting complicated microstructures [1]. It is an essential technique in manufacturing that offers various advantages. Micro EDM uses electro-thermal erosion to fabricate intricate structures on any electrically conductive workpiece irrespective of their mechanical hardness [2], which makes μEDM a highly effective manufacturing technology for conductive or semi-conductive hard materials [34]. Two types of power sources are generally applied in EDM between the tool and workpiece to produce the repetitive electrical sparks, namely RC-based [5] and transistor-based pulse generators [6]. However, in μEDM, RC based pulse generator is preferred over a transistor-based circuit due to its capability of producing low energy yet high-frequency discharge pulses [7]. Despite various advantages, EDM/μEDM has a notable drawback of slow machining rate, mostly contributed by the incidence of the short circuit during the process. A short circuit is an undesirable yet intrinsic phenomenon of EDM/μEDM, which develops mostly because of the physical contact between the tool and debris preventing the desired spark [8]. Minimizing short circuits is one of the key research areas to make the EDM/μEDM process more effective and efficient. One of the ways to achieve this is to use low amplitude vibration to easily flush away the debris formed during machining so that the occurrence of short circuits can be minimized [9,10]. Tong et al. [1] used vibration on the workpiece to carry out μEDM for non-circular microstructures. In their study, Tong et al. [1] observed that machining time could be reduced by ~8x using 1 kHz of vibration frequency at ~5 μm of amplitude. Prihandana et al. [11] investigated the combination of micro powder suspension with ultrasonic vibration for μEDM. However, they did not vibrate the workpiece directly; rather, the vibration was employed on the dielectric liquid through the ultrasonic bath. With the introduction of vibration, the micro powder could not be sedimented at the bottom and always circulated through the dielectric medium that aided the machining process. Moreover, the adherence of debris (formed during the μEDM process) to the workpiece was also reduced and provided an added advantage for the material removal process [11]. Lin et al. [12] combined EDM with ultrasonic tool vibration and assistive magnetic force to improve EDM. The material removal rate (MRR) was improved with the proposed hybrid process compared to the conventional EDM. Also, the surface roughness was improved with the use of vibration and assistive magnetic force during the EDM process. Mastud et al. [13] studied the debris motion in the dielectric fluid for reverse μEDM. It was observed from their study that the end product (micro rod) is free from any adherence of debris to the rod surface if low amplitude vibration is applied at a subsonic frequency of 1 to 6 kHz. Shabgard et al. [14] studied the effect of ultrasonic vibration of the copper tool on the EDM performance of Ti–6Al–4 V alloy. The vibration frequency was kept constant at 20 kHz. The MRR was increased to ~3x to ~4x with the aid of the vibratory tool. However, the improvement became less significant when a higher discharge current (hence discharge energy) was set. The tool wear ratio was also improved by applying the tool vibration at a lower pulse on time. Also, the machining stability factor (an indicator of higher normal discharges) was significantly improved at low energy EDM using tool vibration. Che et al. [15] applied ultrasonic vibration to the workpiece instead of the tool to carry out EDM. Their experimental results suggest that the material removal rate (MRR) was improved significantly as the vibration is applied to the workpiece during the EDM process. However, the surface roughness was observed to be similar for the whole experimental range with and without the application of the workpiece vibration. Liao et al. [16] applied the combination of inclined feed and subsonic vibration for μEDM drilling operation to achieve higher drilling depth due to expected better flushing of the debris. In their experimental study they found that drilling depth increases with the increase of the vibration amplitude until 5 μm. However, above 5 μm of amplitude the drilling depth was found to be reduced due to the excessive short circuit incidents (the tool start to touch the bottom of the workpiece periodically) . Uhlmann et al. [17] used piezo vibrator assisted graphite tool to carry out die sinking EDM on nickel based alloy MARM247. Their [17] findings suggests that increase in the vibration amplitude from 2 μμm to 10 μm slows down the machining rate. Tool wear rate also increased with the increase in vibration amplitude. Kurniawan [18] applied vibration assisted dry EDM for deburring the drilled holes in carbon fiber reinforced polymer (CFRP) composite. The burr removal rate (BRR) was found to be higher if ultrasonic assisted dry EDM was used instead of conventional EDM. Their findings also suggests that at lower capacitor value the ultrasonic vibration was more effective on enhancing the BRR. Marinescu et al. [19] investigated the morphological differences of the surface generated by ultrasonically aided μEDM and conventional μEDM. In this study [19], researchers applied vibration to the tool. Their study concluded that at the optimum condition (power consumed by the ultrasonic chain) the end product's surface roughness was improved with the use of ultrasonic vibration. Shabgard et al. [20] carried out numerical and experimental study to understand the effect of ultrasonic vibration of the tool on the EDM performance. Both studies [20] suggested that ultrasonic vibration of the tool enhances the plasma flushing with increased crater depth and decreased crater radius and recast layer thickness. Hirao et al. [21] also studied the effect of ultrasonic vibration of the tool on the overall EDM performance. The material removal rate (MRR) was increased with vibration frequency until 66.5 kHz and reduced afterward. Interestingly the roughness of the EDMed surface increased as ultrasonic vibration was applied to the tool during the EDM process. Liu et al. [22] conducted a simulation study on the debris flushing mechanism into the EDM zone with the aid of ultrasonic tool vibration. It was observed from the simulation study [22] that with the increase of vibration amplitude the removal mechanism of the debris from the machining zone is enhanced. Similar phenomenon was observed for the vibration frequency. Higher vibration frequency aids the debris removal from the machining zone. However, as the depth of the hole increased (in the simulation study) the debris removal was not effective even with the use of ultrasonic tool vibration. Goiogana et al. [23] investigated ultrasonic vibration of the tool for EDM drilling of blind holes. With the help of vibration the 14 mm drill depth was achieved in 0.8 × 104 s however for conventional EDM drilling the time to drill same depth was found to be 2.5 × 104 s. Geometric accuracy was seen to be similar for conventional EDMed holes and vibration assisted EDMed holes. Recently Li et al. [24] applied ultrasonic circular vibration (UCV) tool to enhance the μEDM performance due to improved capacity of dielectric fluid to remove debris particles from the machining zone. UCV tool helped to improve the diameter consistency for both inlet and outlet of the holes. Choubey et al. [25] carried out finite element modelling to demonstrate that ultrasonic assisted μEDM performed better in terms higher MRR (as compared to conventional μEDM) due to better flushing of debris from the machining zone.

It is reasonable to state, based on the above discussions, vibration-assisted EDM has been investigated by many researchers for both micro [1,11] and macro domains [21,23]. Mostly vibration was applied to the tool [14,17,19,21,23] rather than the workpiece [1,15]. However, based on the above literature study, we could not find any research related to the influence of the vibration on the performance of μEDM with various ranges of its parameters such as discharge energy, EDM speed, etc. This work investigates the effectiveness of ultrasonic vibration as the μEDM's input factors are varied. We also propose a machine learning (ML) based classification model to demonstrate at which processing condition the application of ultrasonic vibration becomes advantageous for the μEDM operation.

2. Materials and methods

This research was carried out using multipurpose micromachining setup DT110 developed by Mikrotools Pte. Ltd. Singapore. The machine has a positioning accuracy of +/− 1 μm per 100 mm of travel length for each stage with a programming resolution of 0.1 μm. The machine uses an RC pulse generator as its power source for the μEDM process. To enhance the μEDM process by applying ultrasonic vibration, we attach an ultrasonic piezo vibrator (typically used for ultrasonic bath) with a workpiece holder using high-strength adhesive. The schematic of the whole experimental setup is shown in Fig. 1. The vibrator was excited using an ultrasonic sinusoidal signal produced by the function generator and later amplified by the power amplifier, as illustrated in Fig. 1. The vibration of the workpiece holder was measured using a laser doppler vibrometer (OMS LaserPoint LP 01) to identify the resonance frequency and amplitude, which were found to be 29.4 kHz and ~1 μm, respectively. Various sets of μEDM experiments were carried out with and without the application of ultrasonic vibration.

Table 1 outlines several factors used for this experimental research. A full factorial experimental design (54 experimental runs) was prepared and carried out by varying μEDM parameters such as voltage, capacitance, feed speed, and vibration status. The vibrator was excited at its resonance frequency (29.4 kHz) for the 27 runs (according to the full factorial design), and it was not excited at all for the other experimental runs. During the machining, the discharge pulses were measured with the help of a high-frequency current transformer (Tektronix CT-1) and a digital oscilloscope (Fig. 1). The machining time was directly calculated from the DT110 μEDM system. The motion controller of the DT110 is designed so that detection of the short circuit causes the motion to be reversed until the short circuit condition becomes an open circuit condition again. Also, during the healthy discharge condition, the motion is paused until the discharge completely clears off the material and an open circuit condition is triggered. It is always desired to minimize the occurrence of short circuits as this causes the reversal motion, which eventually slows down the process. Therefore, it is essential to study the occurrence of short circuits to evaluate the effectiveness of ultrasonic vibration on the μEDM process. The decision-making process on the short circuit, discharge, and the open circuit is carried out by automatically monitoring the electrical condition of the discharge circuit. The machine also creates a distinct beep sound every time it experiences any short circuit that was used to count the number of short circuit incidents during the whole experimental study.

Overcut is an essential parameter of μEDM that was investigated in this research. It is a well-understood phenomenon of EDM/μEDM which occurs due to the circumferential spark between the tool and workpiece. The machined holes were examined under the scanning electron microscope (SEM: JSM-IT100 InTouch Scope™). Later the SEM images of the holes were used to measure the diameter of the entry and exit side of the holes using the ImageJ software [26]. Fig. 2 shows the process of the diameter measurement of the holes from the SEM images. Using the ImageJ software (after proper calibration), a polygon was drawn precisely matching the edge of the entry/exit side of the hole, as shown in Fig. 2. Then, the selected polygon's area was determined from ImageJ, and the diameter was calculated by equating the measured area with that of the standard formula of the circle. A standard frustum of a cone formula was used to measure the removed volume from the machined hole using the data of entry area, exit area, and thickness of the material [27]. Material removal rate (MRR) was then calculated as both removed volume and the machining time were known. The taper angle was calculated from the entry and the exit diameter, and the thickness of the workpiece using the right triangle formulation as explained in [28]. The vertical tool wear is a critical parameter to study for μEDM as it determines the tool's life. At the beginning of each machining process, the tungsten tool's bottom was flattened properly using a process called reverse μEDM [29]. Then the tool was used to detect a reference surface in the Z direction (vertical movement). The Z coordinate was recorded, and the same process of reference surface detection was carried out after each machining. The difference of the two Z coordinates (before and after machining) was taken as the vertical tool wear for that particular experiment.

All the experimental data were tabulated (attached as supplementary material), and the output parameters were divided into two classes (particularly for MRR and tool wear). If the ultrasonic vibration helped boost the MRR and reduce the tool wear with the same input parameters, they were assigned as class 1 or otherwise class 0. Table 2 shows an example of the above classification process with some partial datasets. It can

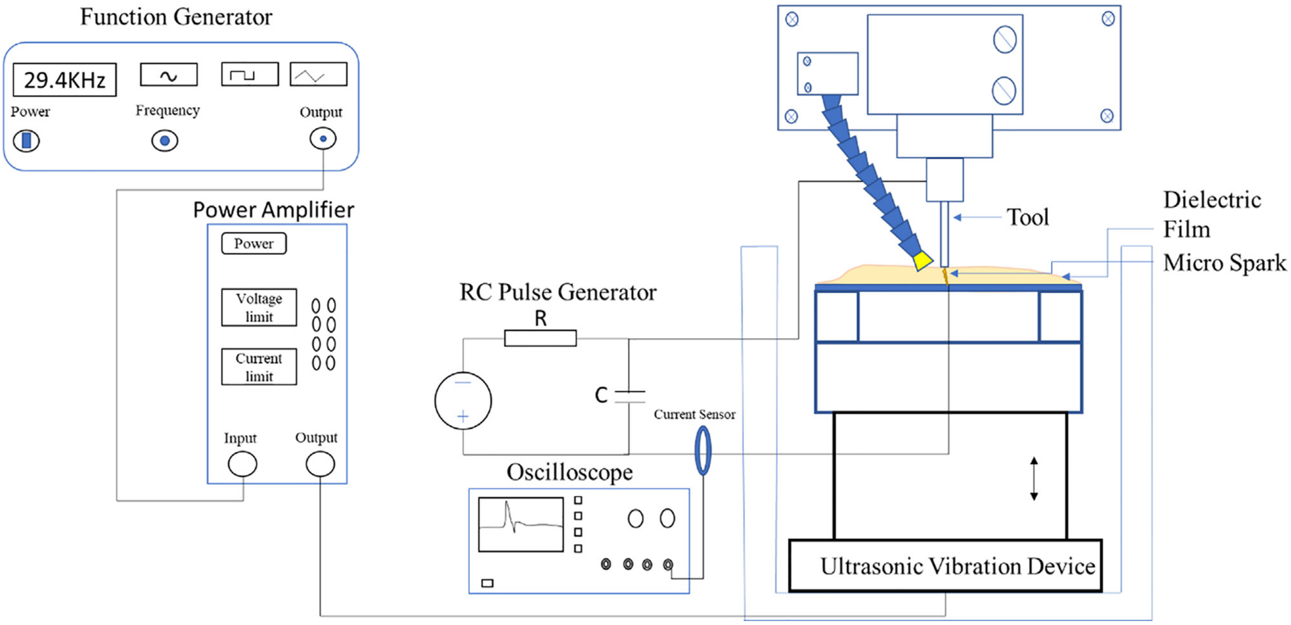

Fig. 1 Schematic of the ultrasonic vibration-assisted µEDM process.

Table 1 Experimental parameters used for this research.

Parameter	Value
Vibration Frequency (kHz)	0, 29.4
µEDM Voltage (V)	80, 100, 120
µEDM Capacitor (nf)	1, 0.1, 0.01
EDM Speed (µm/s)	1, 6, 11
Electrode diameter (mm)	0.3
µEDM spindle speed (rpm)	500
µEDM electrode material	Tungsten (W)
Workpiece material	Stainless Steel (SS 304)
Workpiece thickness(mm)	0.2

be understood from Table 2 that for 80 V, 1000 pF, and 1 µm/s of speed, the MRR was not boosted, nor the tool wear was reduced with the introduction of the ultrasonic vibration during the µEDM process. Hence, it was decided that ultrasonic vibration is not helpful for the above-mentioned set of µEDM parameters and falls under class 0 for MRR and tool wear. However, at 80 V, 100 pF, and 1 µm/s setting, ultrasonic vibration improved both MRR and tool wear; hence this set of parameters falls under class 1. With the whole datasets (class defined), we developed separate classification models for MRR and tool wear to decide in which combination of µEDM parameters ultrasonic vibration becomes beneficial. The classification modeling was carried out using Matlab's classification learner toolbox. We tested several optimizable algorithms and chose the best one with the most accurate prediction. Standard

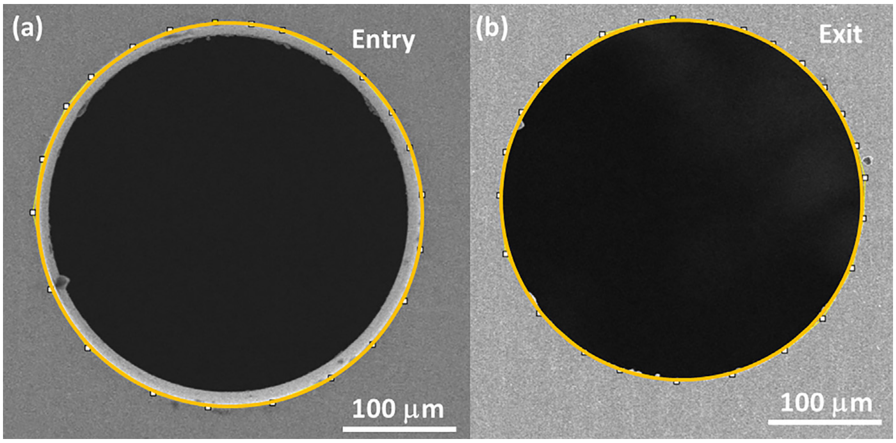

Fig. 2 SEM image of µEDMed holes. The yellow borderline on the edge was added by the ImageJ software to measure the holes' diameter. (a) The entry side of the hole. (b) The exit side of the hole.

Table 2 Example of classification for MRR and tool wear (partial datasets).

Frequency (kHz)	Voltage (V)	Capacitor (pF)	EDM Speed (μm/s)	MRR (mm^3/min)	Class_MRR	Tool Wear,TW (μm)	Class_TW
0	80	1000	1	0.00142	0	50.9	0
29.4	80	1000	1	0.00123		69.4	
0	100	1000	1	0.0017	1	36.7	0
29.4	100	1000	1	0.00177		38.2	
0	120	1000	1	0.00189	0	18.7	0
29.4	120	1000	1	0.00186		34.7	
0	80	100	1	0.00031	1	62	1
29.4	80	100	1	0.00045		60.2	

five-fold cross-validation was carried out to avoid the model's overfitting. Moreover, the capacitor values were converted into the logarithmic scale (to make the spread linear) before developing the model.

3. Results and discussions

This section discusses how and to what extent ultrasonic vibration device influences the μEDM process as the input parameters of the process are changed in various level. MRR, tool wear, short circuits count, overcut, and taper angle are the output variables discussed elaborately in this section.

3.1. Study of material removal rate (MRR) and tool wear (TW)

Material removal rate (MRR) and tool wear (TW) are the two most essential parameters in μEDM. Higher MRR and lower TW are always desirable to ensure faster production and longer tool life. Our experimental observation suggests that for the case of MRR and TW, ultrasonic vibration causes improvement by increasing MRR and reducing TW if a low capacitor value is used for the μEDM power setting. Fig. 3 (a) shows the variation of the MRR with applied voltage and vibration level. However, the capacitor value and the EDM speed are kept constant at their minimum level of 10

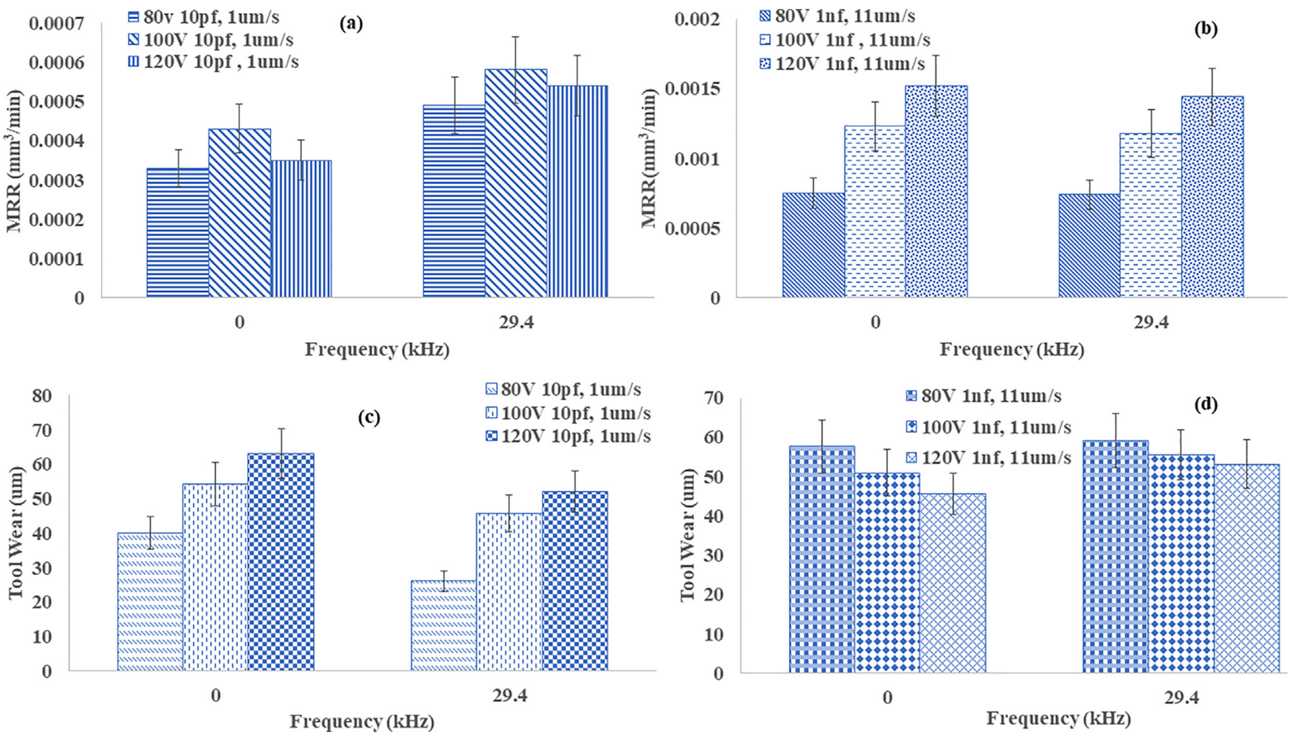

Fig. 3 Variation of MRR and TW with and without ultrasonic vibration at different EDM conditions. (a) MRR variation with open-circuit voltage and vibration status (Capacitor setting was 10pF, and EDM speed was 1um/sec). (b) MRR variation with open-circuit voltage and vibration status (Capacitor setting was 1nF and EDM speed was 11um/sec). (c) TW variation with open-circuit voltage and vibration status (Capacitor setting was 10pF, and EDM speed was 1um/sec). (d) TW variation with open-circuit voltage and vibration status (Capacitor setting was 1nF, and EDM speed was 11um/sec).

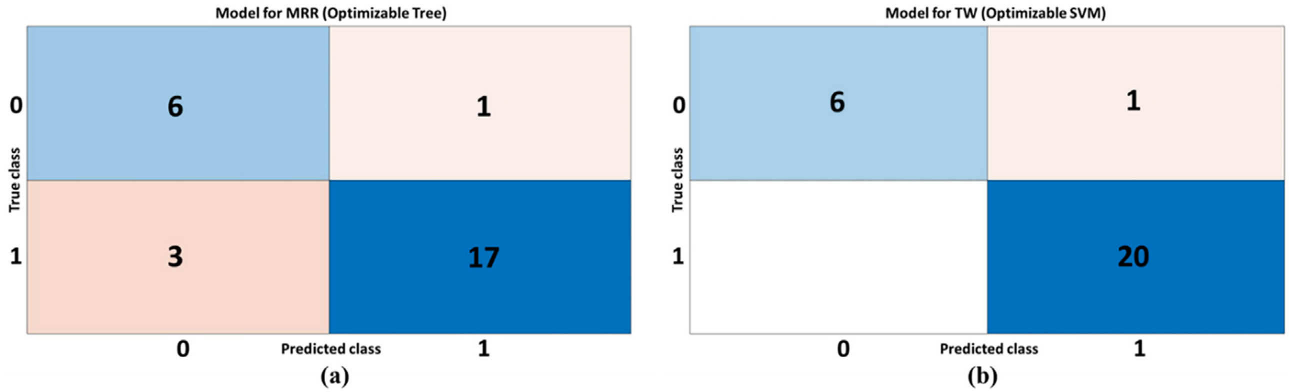

Fig. 4 Confusion matrix for the classification model. (a) For MRR using an optimizable decision tree model. (b) For TW using an optimizable SVM model.

pF and 1 μm/s. Overall the average increase in the MRR (for all voltage levels) was ~46% by applying the ultrasonic vibration device. However, Fig. 3 (b) shows that ultrasonic vibration does not influence the MRR much when the applied capacitor value increased to its highest level of 1nF. A similar phenomenon is observed in Fig. 3 (c) and Fig. 3 (d). Ultrasonic vibration improves the tool wear by reducing it by ~31% at a low capacitor setting (Fig. 3 (c)) whereas, it shows an insignificant impact on the TW as the capacitor setting was increased (Fig. 3 (d)). From the above observation, it can be inferred that at a high discharge energy level (denoted by a higher capacitor setting), the vibration effect becomes considerably minute to

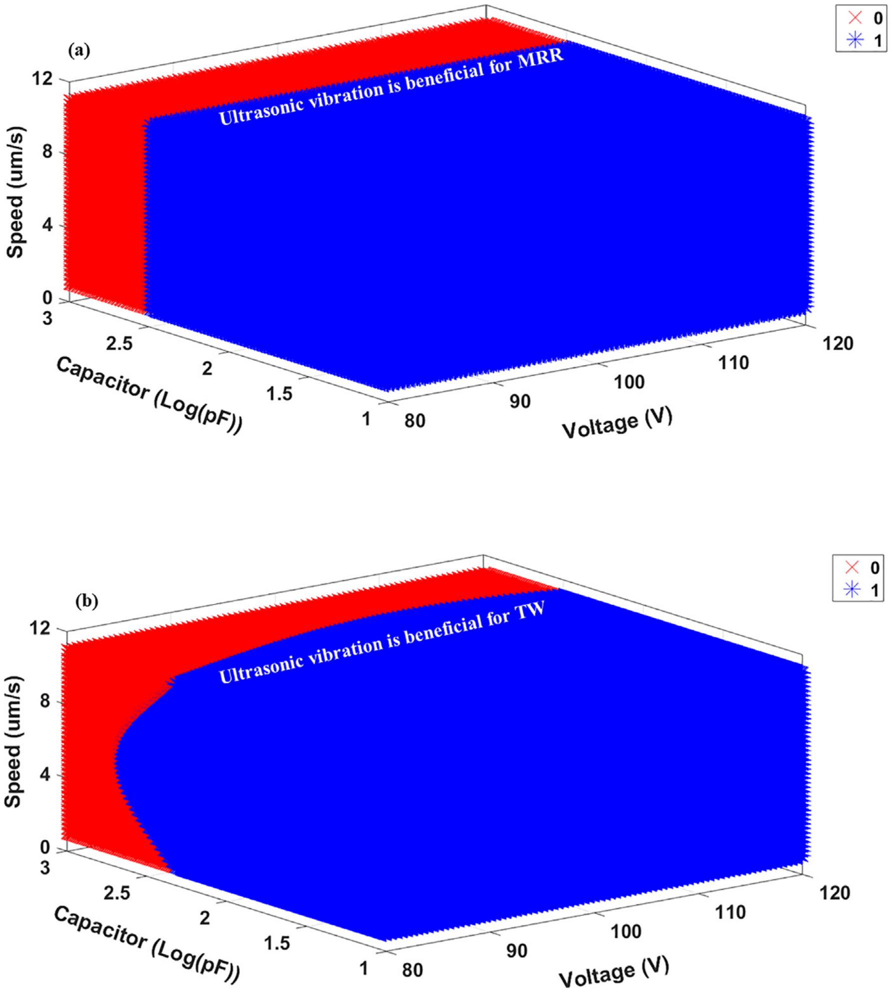

Fig. 5 Decision boundary to show at which μEDM input parameters ultrasonic vibration becomes beneficial (a) for MRR, (b) for TW.

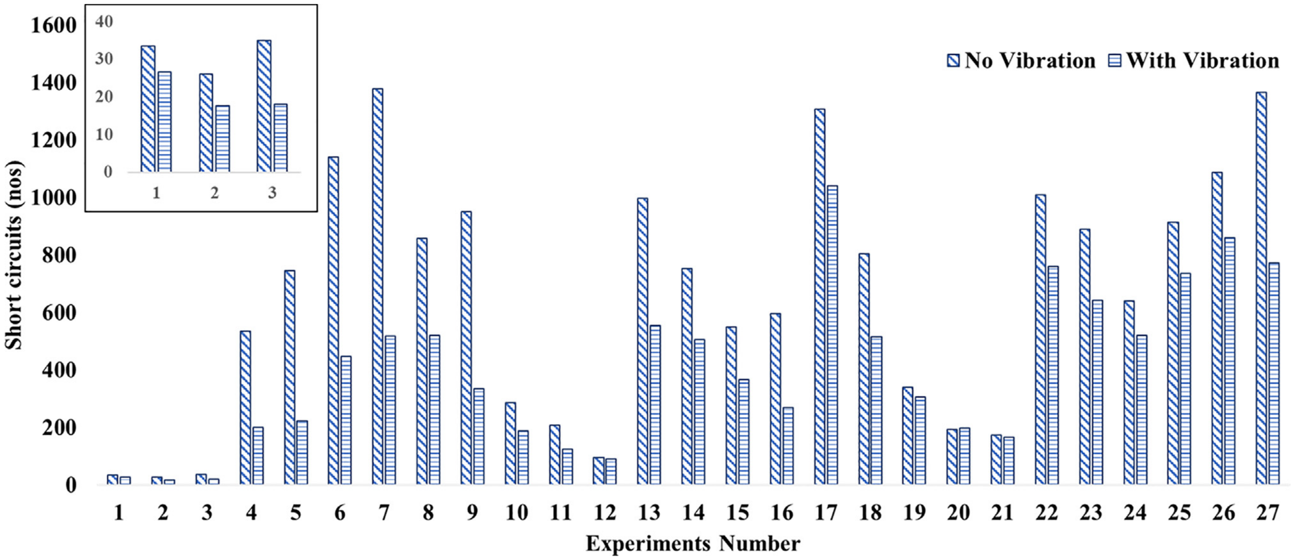

Fig. 6 Absolute number of short circuit incidents during the whole machining for various experimental runs with and without ultrasonic vibrations.

affect the tool wear and MRR substantially enough to overcome the experimental uncertainty.

Therefore, we developed a classification model to create a decision boundary to ascertain which EDM condition makes ultrasonic vibration useful for the process. The definition of the class is explained in Table 2. Once all the classes were defined, the data were fed into the Matlab classification learner toolbox for training the model, with five-fold cross-validation. For the case of MRR, the optimizable decision tree model provided the most accurate prediction with 85.2% of accuracy. In contrast, the classification accuracy with five-fold cross-validation for the TW was 96.3% with the optimizable support vector machine (SVM) model. Fig. 4 shows the confusion matrix for the above two classification models, demonstrating that the TW classification model outperforms the MRR classification model (Fig. 4 (a)) as the latter has three more misclassifications than the former (Fig. 4 (b)). The developed model was then used to predict classes for both MRR and TW with varied µEDM input parameters such as voltage, capacitor, and µEDM speed.

The decision boundary (for both MRR and TW) was plotted with the predicted classes, as shown in Fig. 5. Fig. 5 (a) shows the input region of µEDM parameters where ultrasonic vibration enhances the MRR, which is the capacitor value of less than ~300 pF with any range of set voltage and µEDM speed. For the case of tool wear, Fig. 5 (b) shows that the TW is also lower if the ultrasonic vibration is used at the same zone. Moreover, for the case of TW, the advantageous zone of the ultrasonic vibration covers an even higher capacitor value at a higher µEDM speed. However, it is safe to assume based on Fig. 5 that the ultrasonic vibration is beneficial for µEDM drilling in terms of enhanced MRR and lower and TW when a low capacitor value of (< 300 pF) is selected.

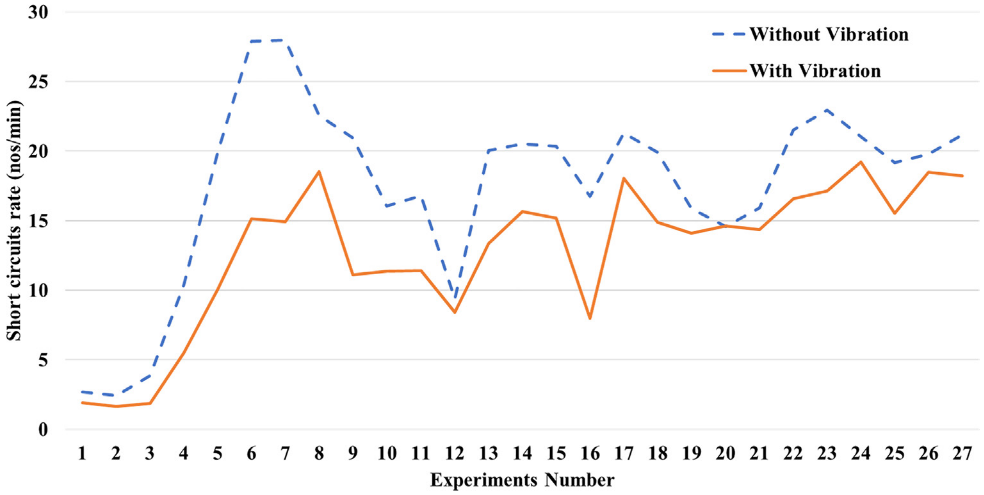

Fig. 7 Rate of short circuit incidents for various machining runs with and without ultrasonic vibrations.

The reason why vibration is effective for some μEDM parametric settings could be explained as follows. In vibration-assisted μEDM, two competing phenomena are concurrently occurring, flushing out of the debris from the machining zone due to vibration and movement of the workpiece away from the tool due to cyclic motion. Effective flushing of debris is predominant for low discharge energy; hence MRR was improved with vibration at low discharge energy. With the increase of the capacitor value, the discharge energy increased significantly as the capacitor was changed in order of magnitude (10 pF, 100 pF, and 1000 pF). Therefore, at higher discharge energy, the μEDM plasma pressure was powerful enough to expel the debris from the machining zone (vibration does not play many roles here). On the other hand, the cyclic motion causes the workpiece to move away from the tool, which deters the vertical sparking, and machining time eventually was increased with the reduction of MRR. Also, as the machining time increased, the tool wear increased due to cir-

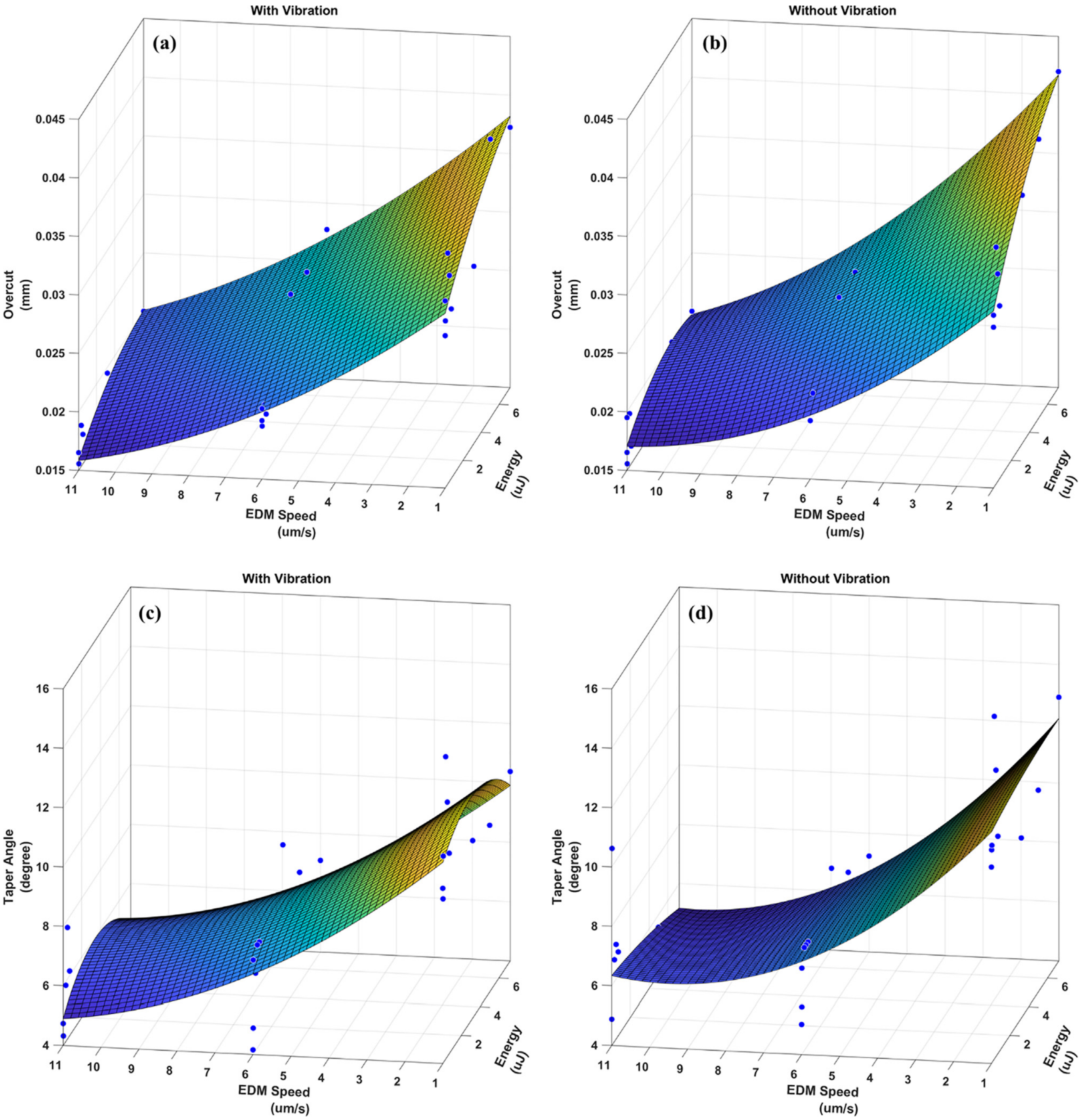

Fig. 8 Surface trend plot for overcut and taper angle. (a) Variation of the overcut for EDM speed and discharge energy when the vibration device was activated. (b) Variation of the overcut for EDM speed and discharge energy when the vibration device was deactivated. (c) Variation of the taper angle for EDM speed and discharge energy when the vibration device was activated. (d) Variation of the taper angle for EDM speed and discharge energy when the vibration device was deactivated.

cumferential sparking when vibration was used with a high value of capacitor set.

3.2. Study of short circuit occurrence

The short circuit is an undesired phenomenon that is very common in the EDM process. A short circuit may occur due to the physical contact between the tool and workpiece/debris. The machine controller reverses the motion to release the tool from the short circuit condition. Hence too much short circuit increases the machining time due to the reversal motion. Ultrasonic vibration enhances the debris removal, thus decreasing the total number of short circuit occurrences and the rate of occurrence, as explained in Fig. 6 and Fig. 7. Fig. 6 and Fig. 7 show that at a high discharge energy setting, both the total number of short circuit incidences and the rate of occurrence are similar for with or without the use of ultrasonic vibration during the μEDM process (e.g., for experiments 1,2,3, 12, and 19–21, where the capacitor setting was 1000 pF.). In the cases of experiments 4 to 6, the rate of short circuit occurrence was very high for conventional μEDM, where a lower discharge energy setting was used (100 pF capacitor). Therefore, the plasma pressure was insufficient to expel the debris; hence the rate of short circuits was high. However, when the ultrasonic vibration device was used (same experiments 4–6), the low amplitude high-frequency vibration aided the debris removal, and the short circuit occurrence rate was reduced significantly Fig. 7. The above finding and the discharge frequency observation result help us explain the effect of vibration on the MRR. As mentioned earlier, a current transformer was used to monitor the frequency of the discharge pulses, which was measured multiple times during each machining process. The result shows that the μEDM pulse frequency was average to ~1 MHz lower if the ultrasonic vibration device was used during the machining. This is because, as the tool approaches the workpiece during the μEDM process, the ultrasonic vibration of the workpiece also periodically causes the workpiece to be away from the tool, which might have reduced the discharge pulse frequency. Another reason could be that the debris was flushed properly from the machined holes (with the assistance of ultrasonic vibration); the chances of secondary spark between the tool circumference

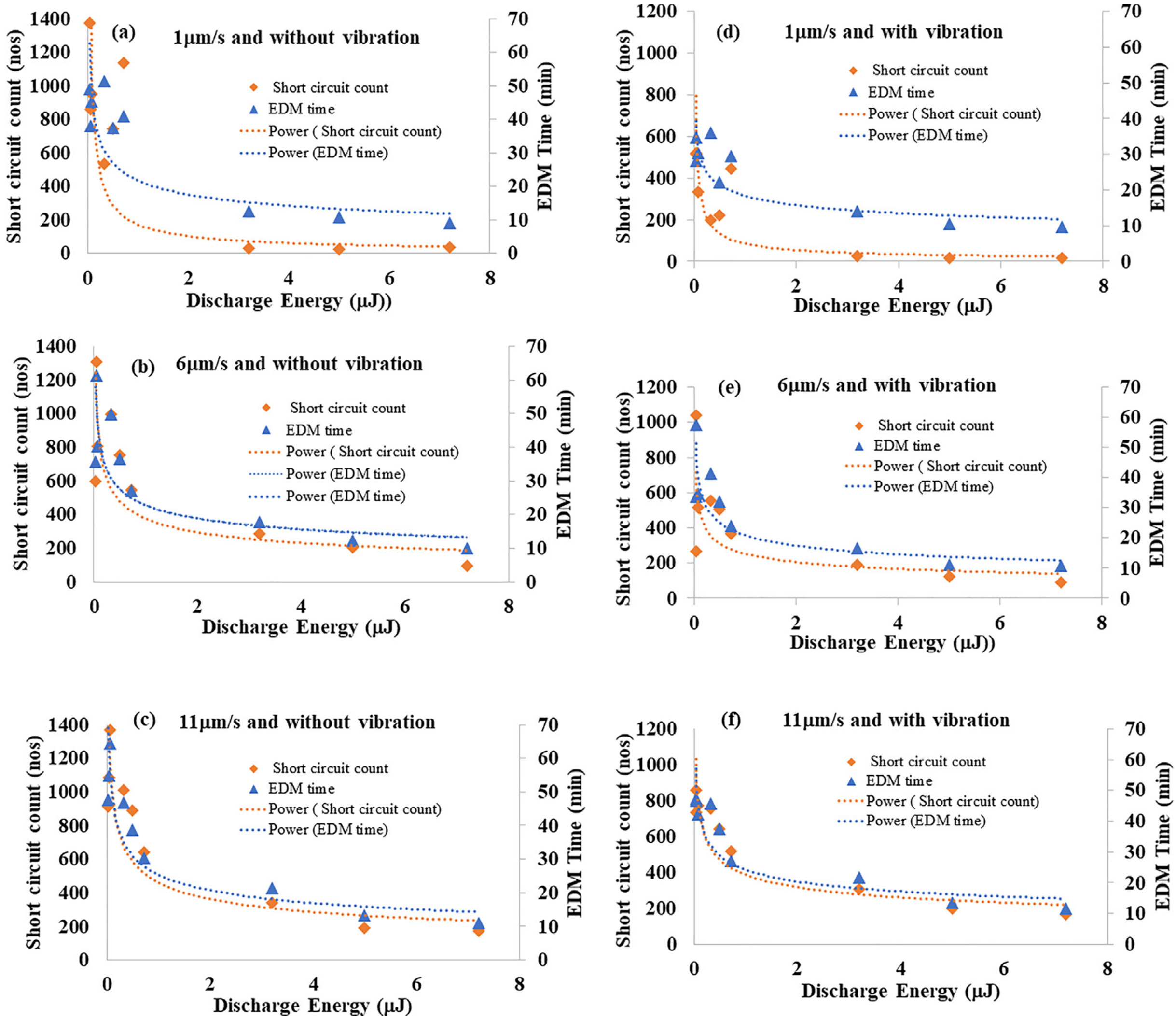

Fig. 9 Variation of EDM time and Short Circuit Count at different EDM speeds and discharge energy with vibration and without vibration assistance.

and debris are also lowered down, reducing the discharge pulse frequency. Now at a low discharge energy setting with a low capacitor value, the reduction of the short circuit is so overpowering that the effect of lower discharge frequency subsides. As a result, overall machining time reduces with the addition of ultrasonic vibration during μEDM. However, at a higher capacitor value, the phenomenon changes as the reduction of the short circuit is not that significant with the addition of the vibration device. Therefore, the effect of higher discharge frequency without the aid of the vibration device (during the μEDM process) is dominant, and the MRR is similar or even higher compared to μEDM with vibration.

3.3. Study of overcut and taperness

In μEDM, researchers always try to minimize two problems: overcut and taperness of the hole. Fig. 8 demonstrates that vibration improves the overcut and taper angle on the finished holes by reducing them. As the vibration was applied, the chance of secondary discharges with the debris was reduced due to enhanced flushing. This phenomenon helped to reduce the overcut as well as the tool wear. Subsequently, the finished holes became straighter with a lesser taper angle because of reduced tool wear. Another interesting observation from Fig. 8 is the decreasing trend of the overcut and taper angle with the EDM speed. As shown in Fig. 9, with the increase in EDM speed, the machining time also increased with vibration Fig. 9 (a,b, and c) and without vibration case Fig. 9 (d, e, and f). Intuitively, the higher machining time usually indicates that the overcut and the taperness increase because of prolonged sparking between the tool and workpiece. However, Fig. 9 also demonstrates that the short circuit count follows the machining time trend. Therefore, it can be inferred from Fig. 9 that a longer machining time is due to reversal motion resulting from short circuit incidents, which did not increase the spark between the tool and workpiece. Instead, it can be further said that the actual interaction time between the tool and workpiece (with discharge) at higher EDM speed reduces. Therefore the overcut and taper angle were found to have decreasing trend with the EDM speed (Fig. 8).

4. Conclusions

Vibration-assisted μEDM has been investigated by many researchers lately. They have investigated the effect of vibration from the sonic range to the ultrasonic range. Researchers also investigated effects by applying vibration to the tool as well as to the workpiece. However, in this paper, we report our new findings related to the effectiveness of vibration as the μEDM input parameters, namely voltage, capacitor, and EDM speed change. The following conclusions can be drawn from this research:

1. Experimentally it was observed that at a higher capacitor value of 1nF with any range of discharge voltage and EDM speed, the vibration device became ineffective in regards to increasing MRR and reduced tool wear. On the other hand, at a low capacitor value of 10 pF, the ultrasonic vibration can help to improve the MRR by over ~40% compared to conventional μEDM. Similarly, the TW was also reduced by over ~30% at a low discharge energy setting by applying the vibration device. Although, the number of short circuit incidents was mostly reduced by applying the vibration device because of the efficient flushing. Even though, at lower discharge energy, the effect was more prominent. The short circuit occurrence rate was also noticeably reduced over the whole spectrum of the experimental setting.
2. A classification model has been developed to define the boundary at which EDM condition vibration device becomes helpful to use. The model takes discharge voltage level, capacitor, and EDM speed as the input to predict if the vibration device enhances the MRR or reduces the tool wear. The model accuracy for MRR and tool wear was 85.2% and 96.3%, respectively.
3. Finally, with the application of the vibration, the machined holes resulted in lesser overcut and taperness at the same EDM condition. This is due to effective flushing of the debris (with vibration), resulting in fewer secondary discharges. As a result, the holes became closer to the tool diameter and straighter.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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