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진동을 이용한 건식 마이크로-WEDM 에 대한 실험적 연구 및 프로세스 최적화

Experimental Study and Process Optimization for Vibration-assisted Dry Micro-WEDM

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This paper presents an experimental study of a vibration-assisted dry micro-wire electrical discharge machining (μ-WEDM) utilized in high precision and micro-manufacturing area. The assisted vibration was applied to the workpiece using a piezoelectric actuator, and high pressure air was injected directly into the machining gap through a nozzle. Investigation experiments were performed to estimate the importance of input parameters and it was observed from experiment results that the width (kerf) of the cutting slot and the machining time were significantly affected by the air injection pressure and input energy. Moreover, it was also observed that there exists an optimal relationship between the machining time and input parameters including the air pressure and vibration frequency and amplitude. Central composite design based experiments were also carried out, and empirical models of the machining time and cutting slot kerf have been developed using the response surface methodology to analyze and optimize the process.

Key Words: Dry Micro-WEDM (건식 마이크로-WEDM), Workpiece Vibration (공작물진동), Machining Efficiency (가공효율), Slot Kerf (슬롯커프)

1. Introduction

Wire electrical discharge machining (WEDM) has been a widely accepted non-contact machining process in the manufacturing industry recently. WEDM using a running wire can cut through a very thick workpiece of electrically conductive materials regardless of its hardness and stiffness. In addition, with the help of computer numerical control (CNC) system, WEDM can cut extremely taper shapes easily. WEDM had been first introduced in the late 1960s on purpose of making tool electrode utilized in electrical discharge machining (EDM) and rapidly become very popular in manufacturing due to its special capability. WEDM is commonly used for fabricating stampings and extrusion tools and dies, fixtures and gauges, prototypes, aircraft and medical parts, grinding wheel form tools and also for the finishing process. Major research activities on WEDM include the WEDM process modeling and optimization to improve the machining efficiency and accuracy and the WEDM process monitoring and control.[1]

One of the most important factors that affect the EDM performances is the flushing of the dielectric where the discharge occurs. Commonly used dielectrics in most EDM applications are hydrocarbons such as kerosene, transformer oils, lubricating oils and synthetic oil. Micro-

EDM using deionized water has also been investigated by a variety of researchers since it can provide higher erosive effects and a safer machining environment. However, EDM in deionized water is just suitable for rough cutting with low accuracy.[2] Recently EDM in gases has received increasing attention due to its advantage of high accuracy and low environmental effect. Kunieda and Furudate presented in their research the investigation for high precision finish cutting using dry WEDM wherein the WEDM process was performed in atmosphere only.[3] High accuracy in finish cutting but low material removal rate (MRR) and streaks over the machined surface were observed from their experimental results. Several researches on dry and near-dry EDM had been carried out in subsequent years.[4-10] In these researches, high pressure gas (in the range of 0.1 to 0.6 MPa) was supplied into the working gap using a slot tool electrode. Higher MRR could be obtained when oxygen was used for flushing comparing to using natural gas, and sucking was found to be more effective than injecting gas.

Among various methods for improving the machining performance of the EDM process, assisted vibration is a popular method and is considered as one of the most effective methods. Kremer et al. noticed in their research that the machining efficiency increased mainly as a results of the increase of the dielectric circulation caused by the ultrasonic vibration of the tool electrode.[11] In dry EDM, according to Xu et al., since the process was performed in gas, the vibration of the electrode accelerated the dropping of melted material and therefore improved the efficiency of the material removal.[12] In WEDM, it was found by Hoang and Yang that higher improvement could be obtained by applying non-ultrasonic vibration to the workpiece compared to applying to the wire electrode.[13]

Dry WEDM is a clean technology and moreover it can provide high accuracy and high surface quality. Therefore, it is necessary to improve the efficiency of this machining technology to expand its applications in the manufacturing industry. Thus, a study on the effect of input parameters and assisted vibration to the machining performance of a dry micro-WEDM has been carried out and is presented in this paper. In this study the effect of different air injection pressures, input energies and vibration parameters to machining time (MT) and machined slot width (kerf) have been investigated. In order to analyze and to optimize the machining process, second-order polynomial models for MT and slot kerf have been developed based on the central composite design (CCD) experiments using the response surface methodology (RSM).

2. System principles and configuration

Electrical discharge is an electro-thermal process occurring in the form of a plasma channel which bridges the distance between the anode and cathode. This plasma channel is developed by a series of collision of electrons, which is excited by a strong electric field between two electrodes, and the atoms of the medium. The length of the electrode gap, where the discharge occurs, depends on the strength of the dielectric fluid. The gap is smaller when a higher strength dielectric is used. Since gases have a much lower dielectric strength compared to dielectric liquids, the gap length of EDM in gases is much higher than that of EDM in dielectric liquids. Moreover, as mentioned in DiBitonto et al., the high density of the liquid is the reason for higher energy and pressure plasma compared to that of gas discharges.[14] Therefore, a low MRR can be observed for EDM in gases.

The improvement of vibration-assisted WEDM in oil has been described in Hoang and Yang. In oil, the flushing of the debris is improved by a high pressure variation in the gap due to the high frequency vibration of the workpiece. In gas, however, the pressure variation caused by vibration is much smaller than in oil. The MRR in this case is mainly enhanced by the inertial force caused by the vibration of the workpiece, which can accelerate the removal of the melted material from the machined surface.

The schematic diagram of the vibration-assisted dry micro-WEDM is shown in Fig. 1. Experiments were conducted on a multi-process micro machine tool (DT110, Mikrotools Pte Ltd., Singapore) with a RC-type micro-WEDM system. In all experiments, a zinc coated brass wire electrode with 70 μm diameter was used to cut 300 μm length slots on 500 μm thick workpieces of grade-5 titanium alloy. The wire was set at a tension of 0.5 N so it can be stable under a high pressure air (0.15 MPa) injected into the gap. The workpiece was coupled with a

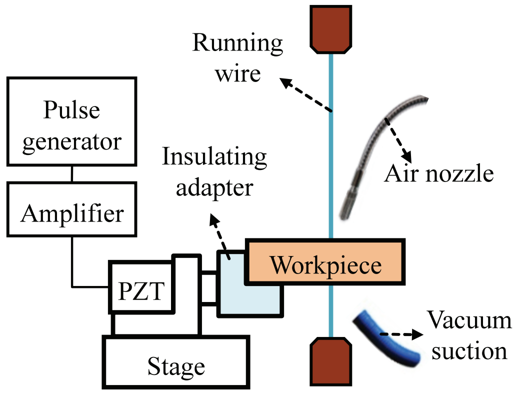


Fig. 1 Vibration-assisted dry µ-WEDM

PZT actuator through an insulated and high stiffness material. Digital rectangular pulses were generated by an arbitrary function generator before being amplified to operate the PZT actuator. In addition, a vacuum machine was used to collect the removed material from the gap.

3. Experiment results and discussion

3.1 Effect of input energy

The input energy for an RC-type EDM process is determined based on the open voltage and the input capacitance.[15] The effect of input energy on machining time at different air injection pressures is described in Fig. 2. Three sets (1nF, 125V), (10nF, 90V) and (10nF, 125V) of (capacitance and voltage) were used to generate three levels of input energy. As can be seen from the figure, the machining time tends to decrease as the input energy increases. The dropping of the machining efficiency of the process which caused by the variation of the air injection pressure increases along with the decrease of the input energy and is very high at a low input energy (7.81 µJ). This proves that the distribution of the energy to electrodes was significantly affected by the high pressure air flow. It was observed also that the further increase of input energy did not improve the machining efficiency but increased the risk of the wire breakage.

In an RC-type discharge process, the energy is charged and stored in the capacitor. This energy is released when the electrode gap is in the discharge range. In micro-EDM, the discharge range is depended mainly on the material of the dielectric. Fig. 3 shows the effect of

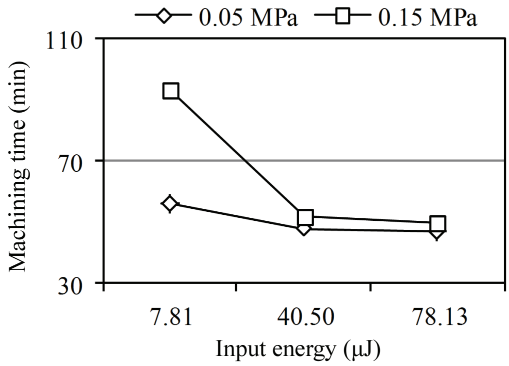


Fig. 2 Effect of input energy on machining time

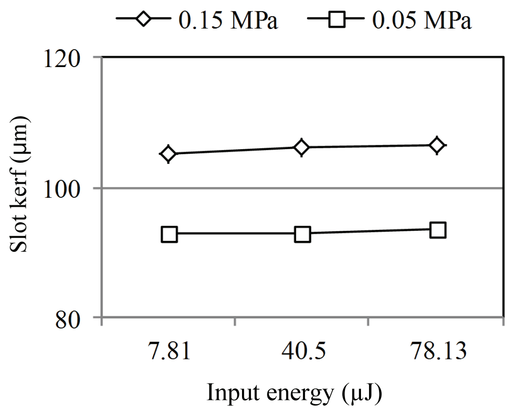


Fig. 3 Effect of input energy on kerf

the energy on the kerf of the dry micro-WEDM process. When the input energy increased, only a very small change in the kerf was observed.

3.2 Effect of air injection pressure

The effect of air injection pressure on machining time is shown in Fig. 4. The machining time increased with the increase of the air injection pressure. This phenomenon is caused by the decrease of the breakdown voltage when the pressure increases according to Paschen's law.[16] Since the product of air pressure and electrode gap was extremely small, the increase of the pressure led to the decrease of the breakdown voltage of the air medium. Thus increased the discharge range and resulted in a higher slot kerf (as shown in Fig. 5) and a longer machining time. Moreover, since the discharges at higher distances are less efficient, the machining time for a unit of material volume also increases.

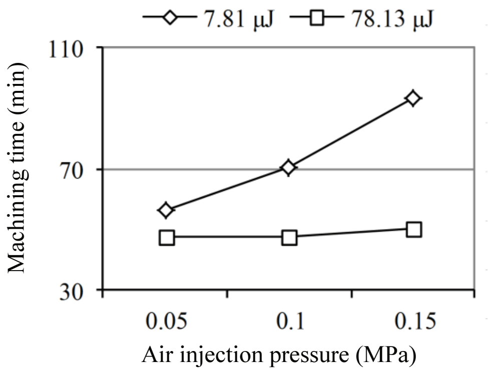


Fig. 4 Effect of air injection pressure on machining time

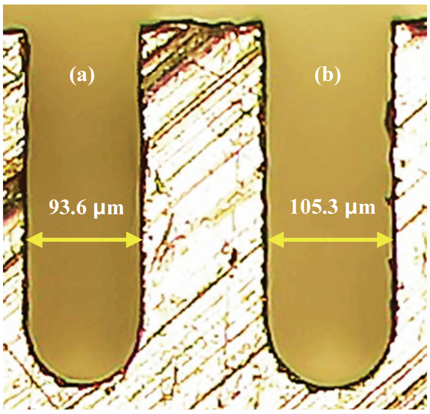


Fig. 5 Kerf of slots cut with (a) 0.05 MPa and (b) 0.15 MPa

3.3 Effect of vibration

In dry EDM, the vibration of the workpiece can improve the removal efficiency of the melted material by the effect of the inertia force. In addition, with vibration the melted materials re-solidified and attached on the machined surface as well as the short circuit can be also reduced. As shown in Fig. 6, the machining time decreased when the vibration frequency increased. Fig. 7 shows the relation between vibration amplitude and machining time at different vibration frequencies. As can be seen from the figure, at each frequency, there exists always an optimum vibration amplitude. This is because the frequency of the feedback system is much smaller than that of the vibration; the workpiece was frequently driven out of the discharge range during the vibration. Thus, for higher amplitude, a higher frequency is required.

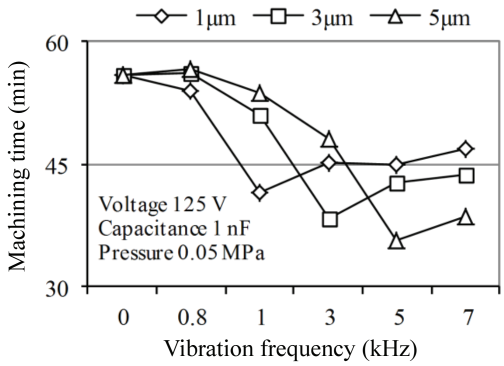


Fig. 6 Effect of vibration frequency on machining time at different vibration amplitudes

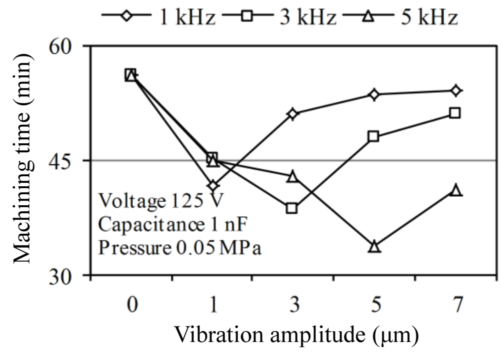


Fig. 7 Effect of vibration amplitude on machining time at different vibration frequencies

4. Modeling and optimization

4.1 Design of experiments

The response surface methodology (RSM) was used to develop empirical models of machining time and slot kerf based on the input parameters as shown in Table 1. Each factor has five levels (corresponding to the code values) which were selected and design based on the central composite circumscribed (CCC) design.[17] Here, the code values (±1.68, ±1, 0) represent the axial points, cube points or factorial points and center point respectively. Since optimal relations between the machining performance and the input parameters have been observed from the experiment results, the second-degree polynomial was selected for the modeling. The CCC design for three factors includes eight factorial points, six axial points and six duplicated center points. The total twenty run, experiment design and results are

Table 1 Control parameters and levels

Code values	Air pressure (MPa)	Vibration frequency (kHz)	Vibration amplitude (μm)
1.62	0.18	7.36	7.36
1	0.15	6	6
0	0.1	4	4
-1	0.05	2	2
-1.62	0.015	0.63	0.63

Table 2 CCC experiment design and results

Run Order	Air Pressure (MPa)	Vib. Freq. (kHz)	Vib. Ampl. (μm)	MT (min)	Kerf (μm)
1	0.1	4	4	32	94.3
2	0.05	6	2	45	89.5
3	0.05	2	6	47	89.1
4	0.05	6	6	46	90.9
5	0.1	4	4	31	95.0
6	0.05	2	2	45	89.7
7	0.1	7.36	4	42	95.7
8	0.015	4	4	54	75.9
9	0.1	4	0.63	48	95.1
10	0.1	4	4	33	95.5
11	0.1	0.63	4	55	95.1
12	0.15	6	6	54	102.6
13	0.18	4	4	60	105.7
14	0.1	4	4	32	94.3
15	0.15	2	6	52	102.8
16	0.1	4	4	33	94.2
17	0.15	2	2	65	101.6
18	0.1	4	4	31	94.6
19	0.1	4	7.36	51	94.4
20	0.15	6	2	52	102

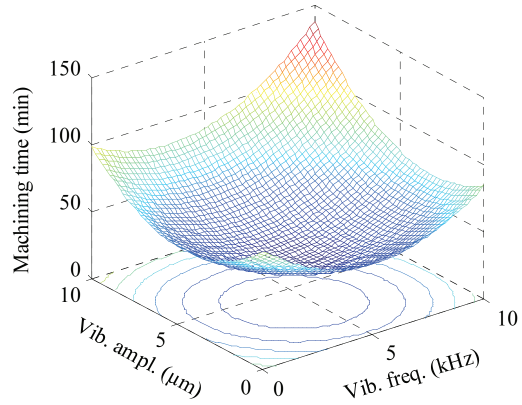
shown in Table 2. The capacitance of 1 nF and voltage of 125 V were hereafter used for all the experiments.

4.2 Response surface model

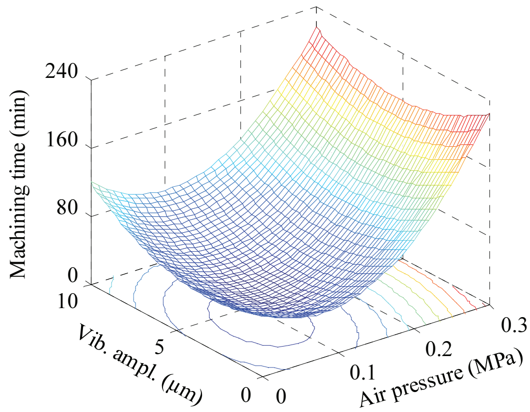
Based on the experiment results shown in Table 2, the second-degree regression polynomials of machining time and slot kerf were derived as shown in Eq. (1) and Eq. (2).

$$\begin{aligned} MT = {} & 103.1 - 497.86x_1 - 12.35x_2 - 11.42x_3 \\ & + 3494.8x_1^2 + 1.33x_2^2 + 1.41x_3^2 \\ & - 12.5x_1x_2 - 17.5x_1x_3 + 0.44x_2x_3 \end{aligned} \tag{1}$$

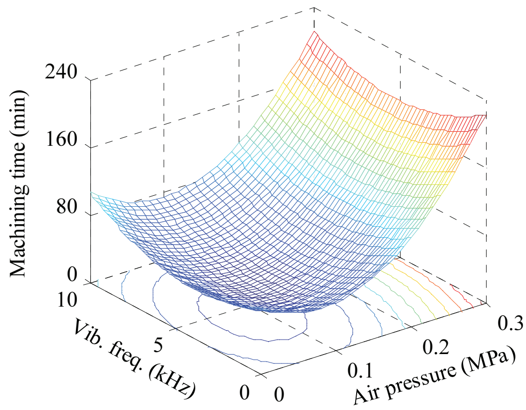
$$\begin{aligned} Kerf = {} & 81.6 + 213.6x_1 - 1.4x_2 - 1.3x_3 \\ & - 324.5x_1^2 + 0.18x_2^2 + 0.1x_3^2 \\ & - 1.7x_1x_2 + 1.2x_1x_3 + 0.04x_2x_3 \end{aligned} \tag{2}$$



(a) Vibration frequency & amplitude



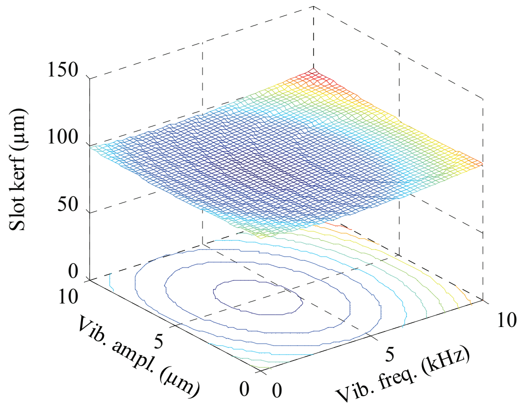
(b) Vibration amplitude & air injection pressure



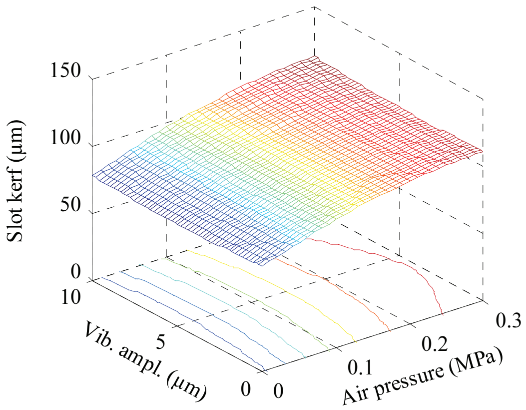
(c) Vibration frequency & air injection pressure

Fig. 8 Machining time versus input parameters

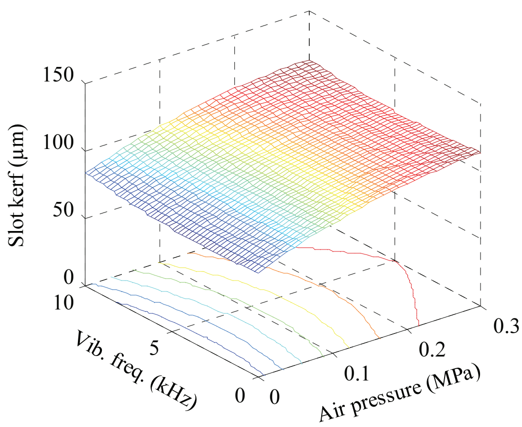
The response surfaces and contour plots of machining time are shown in Fig. 8. From the surface plots, we can observe that there exists always optimal condition to minimize the time of the machining process. Fig. 9 shows



(a) Vibration frequency & amplitude



(b) Vibration amplitude & air injection pressure



(c) Vibration frequency & air injection pressure

Fig. 9 Cutting slot kerf versus input parameters

the response surface and contour plot of the slot kerf. As we can see from this figure, the vibration affects lightly to the kerf of the slot. This is because the kerf of the slot depends also on the cutting speed of the process which

Table 3 Optimization designs

Case	Response	Lower	Target	Upper	Weight
1	MT(min)	0	None	35	1
	Kerf(μm)	89	90	91	1
2	MT(min)	0	None	40	1
	Kerf(μm)	94	95	96	1
3	MT(min)	0	None	45	1
	Kerf(μm)	99	100	101	1

Table 4 Optimum responses

	Case 1	Case 2	Case 3
Air pressure (MPa)	0.07	0.1	0.135
Vibration frequency (kHz)	4.36	3.99	5.63
Vibration amplitude (μm)	3.75	3.89	4.3

varies with the vibration parameters. From both Fig. 8 and Fig. 9, it is observed that the air injection pressure significantly affects to both machining time and the kerf of the cutting slot. Even though further decreases of the air injection pressure below the optimal condition can still reduce the kerf, it also results in a poor flushing condition in the gap. Thus reduces the efficiency of the material removal in the gap and short circuit frequently occurred. Therefore it is necessary to optimize the process to find the best condition for a specific slot kerf but also can improve the efficiency of the system.

4.3 Experimental verification

In order to verify the validity of developed empirical models, verification experiments have been performed.

Three optimization designs were used for the experimental confirmation. Each design targets a selected kerf and searches for an acceptable minimum machining time. The desirability function approach was used for this task. The setup for optimization designs to achieve three selected slot kerfs with accuracy of ±1μm is shown in Table 3. The optimum conditions for each case were obtained using Minitab software and shown in Table 4. The comparisons of confirmation experiment results and predicted values are shown Fig. 10. The experiment results show good matches with the predicted values which prove also that the other unknown factors did not affect the process significantly. In addition, at low air injection pressure, poor flushing condition can cause inaccurate prediction and high discrepancy.

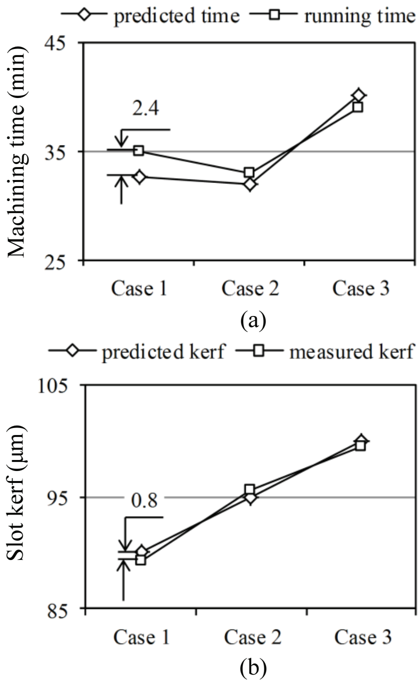


Fig. 10 Comparison of confirmation experiment results and predicted values for (a) machining time and (b) slot kerf

5. Conclusion

In this paper, an experimental study and empirical modeling for machining time and slot kerf have been presented. Important conclusions could be drawn as follow:

- Machining time is significantly affected by the input energy.
- Air injection pressure significantly affects the process such that higher air injection pressure results in a longer machining time and a larger slot kerf.
- The assisted-vibration remarkably improved the machining efficiency of the dry micro-WEDM.
- There exists always an optimal relation between the air injection pressure, the vibration parameters and the machining time.
- The result of confirmation experiments shows good matches to the predicted values which prove that the unknown parameters did not significantly affect the machining process.

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REFERENCES

1. Ho, K. H., Newman, S. T., Rahimifard, S., and Allen, R. D., “State of the Art in Wire Electrical Discharge Machining,” International Journal of Machine Tools & Manufacture, Vol. 44, No. 12-13, pp. 1247-1259, 2004.
2. Jeswani, M. L., “Electrical Discharge Machining in Distilled Water,” Wear, Vol. 72, No. 1, pp. 81-88, 1981.
3. Kunieda, M. and Furudate, C., “High Precision Finish Cutting by Dry WEDM,” CIRP Annals - Manufacturing Technology, Vol. 50, No. 1, pp. 121-124, 2001.
4. Kunleda, M., Miyoshi, Y., Takaya, T., Nakajima, N., ZhanBo, Y., and Yoshida, M., “High Speed 3D Milling by Dry EDM,” CIRP Annals - Manufacturing Technology, Vol. 52, No. 1, pp. 147-150, 2003.
5. ZhanBo, Y., Takahashi, J., and Kunieda, M., “Dry Electrical Discharge Machining of Cemented Carbide,” Journal of Materials Processing Technology, Vol. 149, No. 1-3, pp. 353-357, 2004.
6. Kao, C. C., Tao, J., and Shih, A. J., “Near Dry Electrical Discharge Machining,” International Journal of Machine Tools and Manufacture, Vol. 47, No. 15, pp. 2273-2281, 2007.
7. Saha, S. K. and Choudhury, S. K., “Experimental Investigation and Empirical Modeling of the Dry Electric Discharge Machining Process,” International Journal of Machine Tools and Manufacture, Vol. 49, No. 3-4, pp. 297-308, 2009.
8. Fujiki, M., Ni, J., and Shih, A. J., “Investigation of the Effects of Electrode Orientation and Fluid Flow Rate in Near-dry EDM Milling,” International Journal of Machine Tools and Manufacture, Vol. 49, No. 10, pp. 749-758, 2009.
9. Govindan, P. and Joshi, S. S., “Experimental Characterization of Material Removal in Dry

Electrical Discharge Drilling," International Journal of Machine Tools and Manufacture, Vol. 50, No. 5, pp. 431-443, 2010.
10. Joshi, S., Govindan, P., Malshe, A., and Rajurkar, K., "Experimental Characterization of Dry EDM Performed in a Pulsating Magnetic Field," CIRP Annals - Manufacturing Technology, Vol. 60, No. 1, pp. 239-242, 2011.
11. Kremer, D., Lebrun, J. L., Hosari, B., and Moisan, A., "Effects of Ultrasonic Vibrations on the Performances in EDM," Annals of the CIRP, Vol. 38, No. 1, pp. 199-202, 1989.
12. Xu, M. G., Zhang, J. H., Li, Y., Zhang, Q. H., and Ren, S. F., "Material Removal Mechanisms of Cemented Carbides Machined by Ultrasonic Vibration-assisted EDM in Gas Medium," Journal of Materials Processing Technology, Vol. 209, No. 4, pp. 1742-1746, 2009.
13. Hoang, K. T. and Yang, S. H., "A Study on the Effect of Different Vibration-assisted Methods in Micro-WEDM," Journal of Materials Processing Technology, Vol. 213, No. 9, pp. 1616-1622, 2013.
14. DiBitonto, D. D., Eubank, P. T., Patel, M. R., and Barrufet, M. A., "Theoretical Models of the Electrical Discharge Machining Process. I. A Simple Cathode Erosion Model," Journal of Applied Physics, Vol. 66, pp. 4095-4103, 1989.
15. Wong, Y. S., Rahman, M., Lim, H. S., Han, H., and Ravi, N., "Investigation of Micro-EDM Material Removal Characteristics using Single RC-pulse Discharges," Journal of Materials Processing Technology, Vol. 140, No. 1-3, pp. 303-307, 2003.
16. Husain, E. and Nema, R. S., "Analysis of Paschen Curves for Air, N2 and SF6 Using the Townsend Breakdown Equation," IEEE Transactions on Electrical Insulation, Vol. 17, No. 4, pp. 350-353, 1982.
17. Myers, R. H. and Montgomery, D. C., "Response Surface Methodology: Process and Product Optimization using Designed Experiments," 2^{nd} ed., Wiley, pp. 321-335, 2002.