DOI: 10.1007/s12541-014-0449-z

Machining Characteristics of Hybrid EDM with Ultrasonic Vibration and assisted Magnetic Force

Yan-Cherng Lin[1,#], Fang-Pin Chuang[2], A-Cheng Wang[3], and Han-Ming Chow[1]

1 Department of Mechanical Engineering, Nan Kai University of Technology, Nantou County 54243, Taiwan
2 Department of Industrial Management, Nan Kai University of Technology, Nantou County 54243, Taiwan
3 Department of Mechanical Engineering, Chien Hsin University of Science and Technology, Taoyuan, 32097, Taiwan
Corresponding Author / E-mail: ycline@nkut.edu.tw, TEL: +886-49-256-3489, FAX: +886-49-256-1401

KEYWORDS: EDM, Hybrid process, Magnetic assisted force, Ultrasonic vibration

In this investigation, an ultrasonic vibration and an assisted magnetic force are integrated with the electrical discharge machining (EDM) to develop a hybrid process of EDM with ultrasonic vibration and assisted magnetic force (EDMUVAMF), and then the hybrid process is adopted to explore the effects of the main machining parameters on the material removal rate (MRR), electrode wear rate (EWR), surface roughness (SR) and morphologies of the machined surface in machining SKD 61 mold steels. Moreover, the effects on expelling the debris from the machining gap are also studied via evaluating the discharge waveforms, and analyzing the morphology of the machined surface. The bottleneck correlated with large area using EDM process would be overcome when the optimal parameters of the hybrid process of EDMUVAMF is obtained. From the experimental results shown, the hybrid process of EDMUVAMF can improve the machining performance. The MRR was increased significantly and the SR was reduced to ameliorate the machining efficiency and machined surface quality. The hybrid process revealed the potential for the applications in large area via EDM technique.

Manuscript received: April 15, 2013 / Revised: February 3, 2014 / Accepted: May 7, 2014

NOMENCLATURE

EDM = electrical discharge machining
USV = ultrasonic vibration
AMF = assisted magnetic force
EDMUVAMF = hybrid process of electrical discharge machining with ultrasonic vibration and assisted magnetic force
MRR = material removal rate
EWR = electrode wear rate
SR = surface roughness

1. Introduction

Electrical discharge machining (EDM) is one of the non-conventional machining processes. Generally, an electrode and a workpiece are submerged in dielectric fluids, such as kerosene and deionized water. The dielectric strength of machining media collapses in a gap between the tool electrode and the workpiece when an appropriate electrical power is applied. A discharge column is formed by ionization when the tool electrode gradually advances towards the workpiece and a suitable gap is formed in which the electrical field strength is increased. An extremely elevated temperature is produced by ionization within the discharge column. A small amount of the workpiece and the tool electrode are vaporized and melted because of the high temperature within the spark spots. A local impulsive force is produced by a dielectric fluid explosion that is caused by thermal expansion, and the melted materials are ejected from the machined surface by this impulsive force. Material removal mechanisms, such as vaporization, melting and expulsion of the dielectric remove surplus material in the EDM process. The machining characteristics of the EDM process do not depend on mechanical properties, such as tensile strength, hardness and toughness, so the EDM process is eminently suited to shaping difficult-to-machine materials, such as mold steels, ceramics and composites.[1-3] As a result, there have been many studies of the machining performance of the EDM process for various advanced materials and these have found many sophisticated industrial applications.[4,5] In the last decade, studies of the EDM process have mainly focused on improvements in machining efficiency, machining precision, quality of machined surface and machining stability.[6-8] Since there is no direct contact between the tool electrode and the workpiece, the machining force in the EDM process is quite small. Consequently, the EDM process is generally considered to be suitable for a fabrication of complex, precise and miniature components.[9-12]

Several studies have investigated effects of dielectric flushing and mechanisms for machining debris ejection in the EDM process.[13,14] In order to improve the expulsion of debris and to prevent the debris from becoming clogged in the machining gap, several studies have added ultrasonic vibration mechanisms by using electrodes (either the tool electrode or the workpiece) or dielectric fluids to avoid the accumulation of debris and to maintain the stability of the EDM process.[15-17] The results of these studies suggest that reducing the accumulation of debris in the machining zone improved the machining efficiency of the EDM process. The combination of EDM with USM prevented the accumulation of debris and improved the machining efficiency in modifying the machined surface. The experimental results suggested that the stability of the EDM process, the machining efficiency and the surface integrity were all improved. Surface cracks were more obvious in conventional EDM than that in magnetic force assisted EDM. Since magnetic force assisted EDM would facilitate the expulsion of machining debris and would reduce the probability of abnormal electrical discharge, the surface cracks were relatively fewer on the machined surface.

The ability to expel debris from the machining gap is crucial to maintain the stability of the EDM process, so the machining efficiency and the surface quality are directly affected by the effectiveness with which debris is expelled. This study develops a hybrid process of EDM with ultrasonic vibration and magnetic assisted force (EDMUVAMF). The benefits of the hybrid process are determined and the effects of the main machining parameters for this hybrid process on the machining characteristics, such as material removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR) are also thoroughly examined, so that a reliable hybrid process for modern industrial applications was established.

2. Experimental Method

2.1 Experimental materials

The workpiece material was SKD 61 steel, which is widely used in the die and mold manufacturing industries. For detection of the discharge waveform, dimensions of 110 mm × 110 mm × 8 mm were used. In order to study the machining characteristics, dimensions of 55 mm × 55 mm × 8 mm were used. The specimens were initially milled and ground to guarantee parallelism for each experiment. Table 1 lists the chemical composition of SKD 61 steel. The electrode material was electrolytic copper, which is the most common material used as a tool electrode in the EDM industry. The electrode dimensions were 50 mm and 100 mm squares of 8 mm thickness. In addition, the front face of the electrode was ground on a plate, using 600, 800 and 1200 mesh grit emery paper, to guarantee an equivalent surface finish and flatness for each electrode. Table 2 shows the essential properties of electrolytic copper. A commercial dielectric was used as the working fluid and a self-built tank was equipped to maintain the height of the sparking spots at 50 mm above the top of the workpiece.

Table 1 Chemical composition of SKD 61

Element	C	Si	Mn	Cr	Mo	V
wt.%	0.32-0.42	0.8-1.2	<0.5	4.5-5.5	1.0-1.5	0.8-1.2

Table 2 Essential properties of copper electrode

Essential properties	Descriptions
Specific gravity (g/cm^3)	8.94
Melting range (°C)	1065-1083
Thermal conductivity (W/m·K)	388
Specific heat (J/kg·K)	385
Thermal expansion coefficient (1/°C)	16.7×10^{-6}
Electrical resistivity (Ω·cm)	1.7×10^{-6}

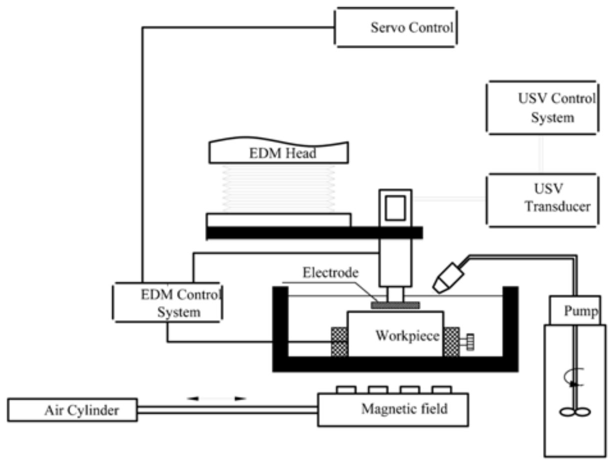

Fig. 1(a) Experimental setup of the hybrid process

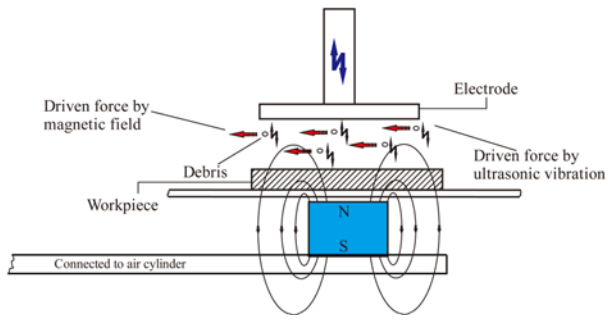

Fig. 1(b) Schematic diagram of the driven forces on the debris within the machining gap of the hybrid process

2.2 Experimental equipment and procedure

A commercial die-sinking EDM machine with a transistor circuit was used for this study. The EDM experiments determined the benefits of the developed hybrid EDMUVAMF process and the effects of the hybrid process parameters on the machining characteristics in machining SKD 61 steel. The self-designed ultrasonic vibration apparatus was attached to the column of EDM machine. The magnetic assisted device integrated a tank and a fixture. High-intensity permanent magnets were also incorporated with a rapidly reciprocating

Table 3 Machining conditions of the experimental works

Working conditions	Descriptions
Workpiece	SKD 61
Electrode	Electrolytic copper
Polarity	Positive (+): Cu(+), SKD61 (−) Negative (−): Cu(−), SKD61 (+)
No-load voltage	260 V
Servo reference voltage	40 V
Peak current	3, 9, 18, 36 A
Pulse duration	100, 200, 300, 400 μs
Off time	75, 100, 200, 300 μs
Magnetic flux density	0.3 T
Ultrasonic amplitude	40 μm
Ultrasonic frequency	17.5~22.5 kHz
Working time	30 min

motion cylinder and positioned on the bottom of the fixture. Fig. 1(a) illustrates the experimental setup for the hybrid EDMUVAMF process. Fig. 1(b) demonstrates the schematic diagram of the driven forces on the debris within the machining gap of the hybrid EDMUVMF process.

The machining characteristics, such as the material removal rate (MRR, mm^3/min), the electrode wear rate (EWR, mm^3/min) and the surface roughness (SR, Ra/mm), were chosen to evaluate the effects of the machining parameters for the hybrid EDMUVAMF process. The workpiece and the electrode specimens were weighed using a precision electronic balance (Precisa XT 220A) with 0.1 mg resolution in order to determine the variation before and after each experiment. The variations were used to calculate the MRR and the EWR. The measurement of the surface roughness was performed using a precision profilometer (Mitutoyo SJ-401) to assess the quality of the machined surface. The surface roughness values were determined by averaging five measurements, which were obtained stochastically at different positions. A high frequency oscilloscope was connected to the two terminals (the tool and the workpiece) to detect the waveforms of the discharge current and the voltage during the process. The discharge waveforms were then used to determine the stability of the gap for the hybrid EDMUVAMF process. The surface integrity was also determined using a scanning electron microscope (SEM) in order to evaluate the effect of the machining parameters on the variation of the surface topography.

2.3 Experimental conditions

The essential parameters such as peak current (I_p), pulse duration (t_p), machining polarity (P), the type of machining media (Type) and the pressure of the air jet (AP), were varied in order to determine their effects on the machining characteristics. The machining time for each experiment was 30 min. The details of the experimental conditions are listed in the Table 3.

3. Results and Discussion

3.1 Effect of the developed hybrid process

Fig. 2 shows a comparison of the discharge waveforms in discharge current and the voltage for conventional EDM and for the hybrid EDMUVAMF process. This figure shows that the conventional EDM

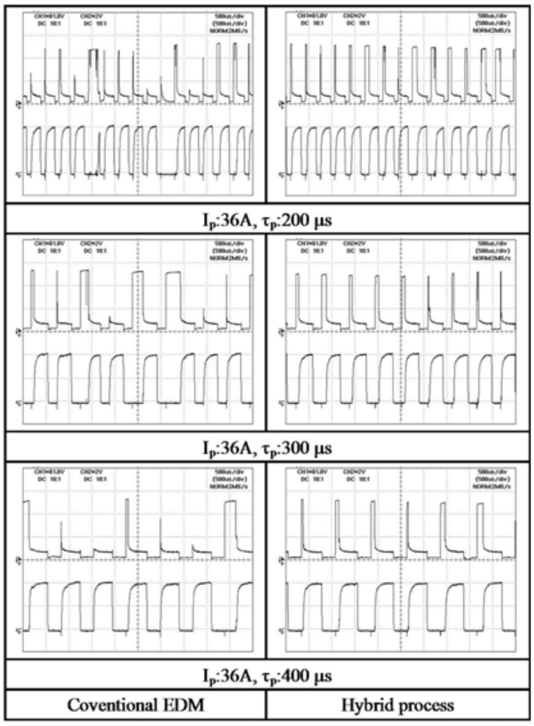

Fig. 2 Discharge waveforms of conventional EDM and the hybrid process

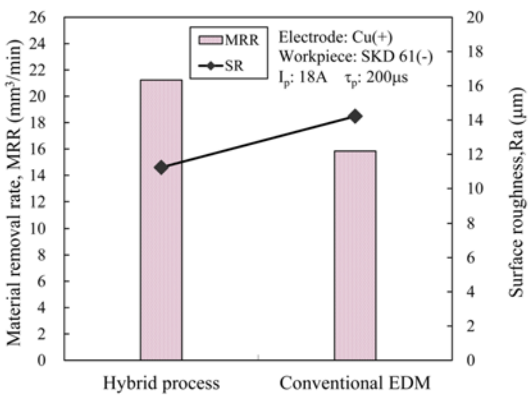

Fig. 3 Comparison in machining characteristics of conventional EDM with the hybrid process

process gradually encountered problems in expelling the debris from the machining gap when the working time was prolonged to a specific value. In general, these problems in expelling debris would become relatively more severe when a large area was machined using the EDM process. The aggregated debris in the machining gap decreased the stability of the EDM process. The discharge waveforms demonstrate that arcing and even shorting were easily possible when the discharge energy was increased to a specific value (larger than 36 A). Arcing occurred because the machining gap did not recover to its initial isolated condition, the stability of the machining gap was degraded and concentrated sparks were easily produced in the following EDM process. This instability of the machining gap not only deteriorated the machining efficiency, but also degraded the surface integrity. The hybrid EDMUVAMF process obviously increased the stability of the machining gap because debris was more efficiently expelled and the pyrolytic carbon was prevented from accumulating in the machining gap.

Fig. 3 shows comparisons of the MRR and the surface roughness for the developed hybrid EDMUVAMF process and conventional EDM under identical discharge energy conditions. These experimental results show that the MRR for the hybrid EDMUVAMF process was greater than that for conventional EDM. The MRR of the hybrid EDMUVAMF process was 34% greater than that for conventional EDM and the surface roughness was reduced by 21%. These experimental results confirm that the hybrid EDMUVAMF process, which incorporated ultrasonic vibration to prevent the aggregation of debris within the machining gap, produced a more stable EDM process. Magnetic force assistance also facilitated the expulsion of debris. This hybrid EDMUVAMF process improved the machining efficiency and the surface finish and was suitable for the machining of large areas.

3.2 Material removal rate

Fig. 4 shows a comparison of the MRR for various peak currents and pulse durations for the hybrid EDMUVAMF process. These experimental results show that the MRR increased as the peak current was increased. This demonstrates that the obvious material removal mechanisms, such as vaporization and melting, were generated within the machining gap as the peak current became greater. Therefore, the MRR increased as the peak current was increased. Furthermore, the MRR increased until the peak value was achieved as the pulse duration was increased, and after which the MRR decreased. In general, the diameter of the discharge column became greater as the pulse duration increased. The large discharge column facilitated the material removal mechanisms for the EDM process, such as vaporization and melting. Therefore, the MRR increased as the pulse duration was increased. When the pulse duration reached a threshold value, the MRR begins to decrease because of the reverse effect on discharge energy variation within the discharge spots. Fig. 5 shows the effect of machining polarity on the MRR. These experimental results show that positive polarity (Cu(+), SKD61(−)) resulted in a relatively large MRR. The cathodic polarity received more discharge energies for long pulse durations, and then the vaporing and melting would be more violent. Thus, the positive polarity obtained obvious material removed effects. Consequently, the MRR firstly increased not only the positive polarity but also the negative polarity, and further extended the pulse duration beyond the threshold value would obtain a reduction trend in the MRR.

3.3 Electrode wear rate

Fig. 6 shows a comparison of EWR for various peak currents and pulse durations for the hybrid EDMUVAMF process. These experimental results show that the EWR increased with peak current and decreased as the pulse duration prolonged. In general, the EWR was affected similarly to the MRR. The EWR increased with the MRR and vice versa. Therefore, a large peak current induced massive spark energies released within the machining zone, which also resulted in a large EWR during the EDM process. However, for long pulse durations, the EWR slightly decreased because the decrease in the spark energy density was caused by the increase in the diameter of the discharge column. Fig. 7 illustrates the effect of machining polarity on

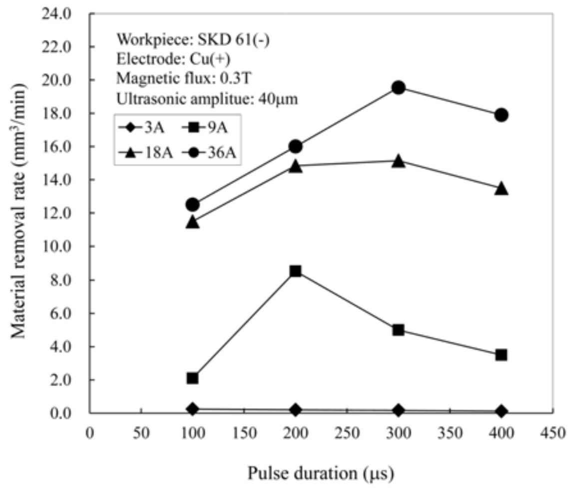

Fig. 4 Relationships of the hybrid process between pulse duration and MRR under various peak currents

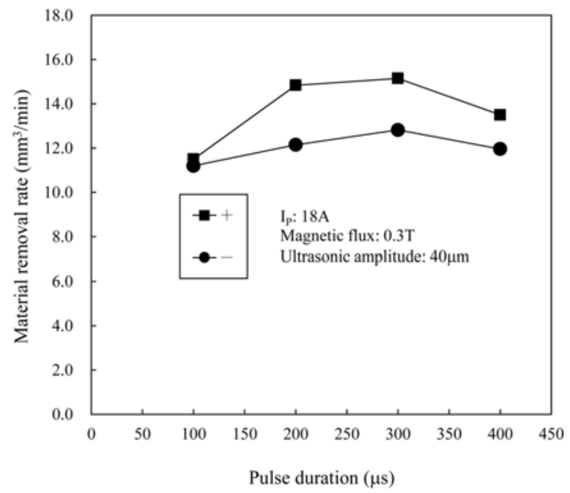

Fig. 5 Relationships of the hybrid process between pulse duration and MRR under different polarities

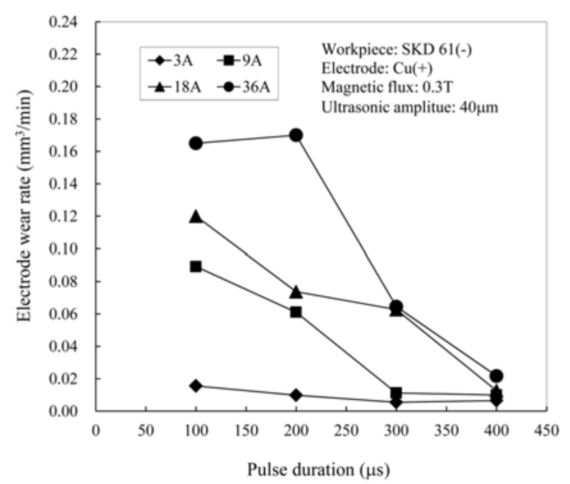

Fig. 6 Relationships of the hybrid process between pulse duration and EWR under various peak currents

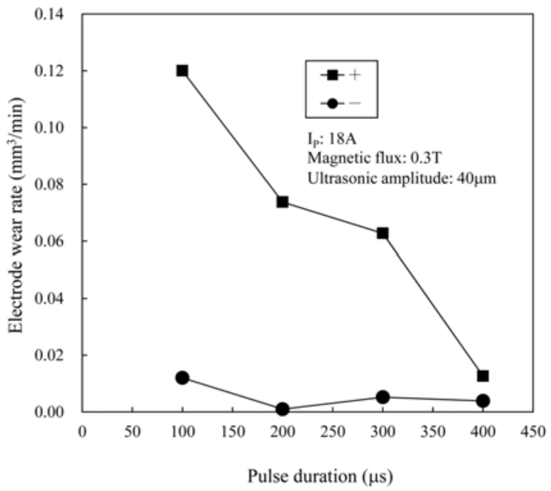

Fig. 7 Relationships of the hybrid process between pulse duration and EWR under different polarities

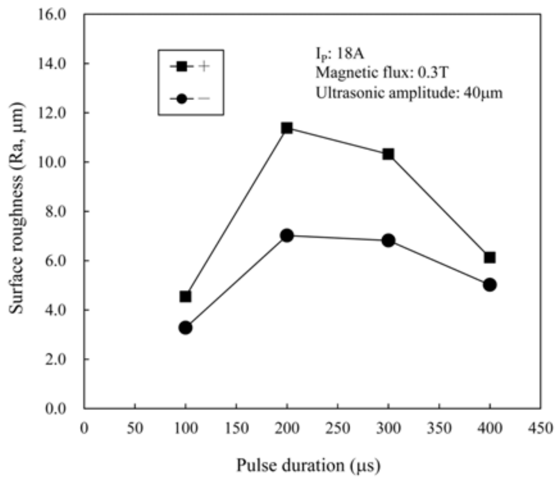

Fig. 9 Relationships of the hybrid process between pulse duration and surface roughness under different polarities

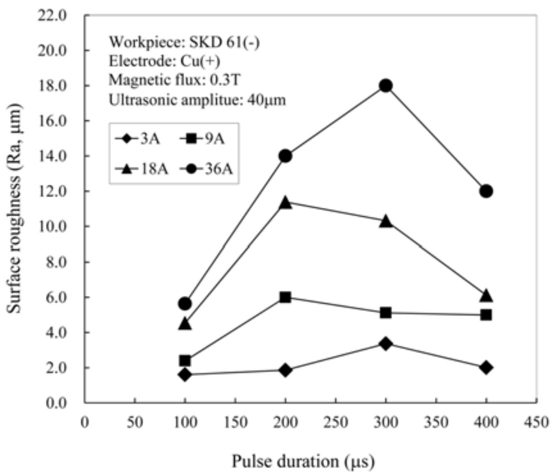

Fig. 8 Relationships of the hybrid process between pulse duration and surface roughness under various peak currents

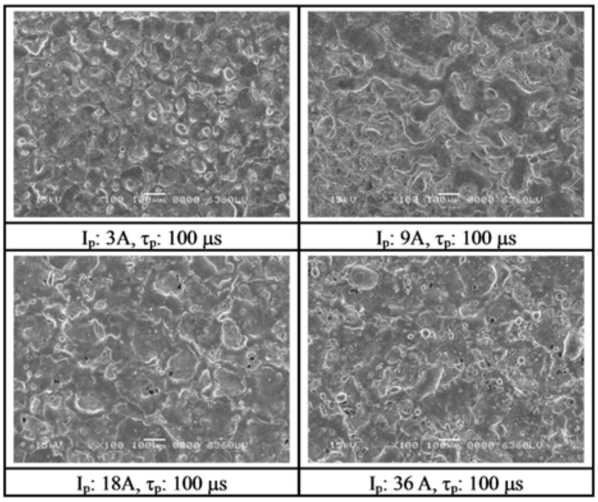

Fig. 10 Micrographs of machined surface obtained by the hybrid process with various levels of discharge energy

the EWR. These experimental results show that the EWR for positive polarity machining is higher than that for negative polarity machining. In addition, negative machining polarity produced a very low EWR during the process.

3.4 Surface roughness

Fig. 8 shows a comparison of SR for various peak currents and pulse durations for the hybrid EDMUVAMF process. These experimental results show that the SR increased as the peak current was increased and that the SR also firstly increased when the pulse duration was increased. When the SR reached a peak value, the SR displayed a reduced tendency with further increasing in pulse duration for a specific peak current. More spark energies were generated within a single pulse during the EDM process as the peak current and pulse duration were increased, so the effect on the material removal during EDM was obvious. Larger and deeper discharge craters were produced on the machined surface and the surface integrity was coarser. Therefore, the SR increased when the peak current and pulse duration were increased for removing more materials, so relatively large and deep discharge craters were produced on the machined surface. In general, the threshold point at which the SR begins to decline depends on the value of the pulse duration, so longer pulse duration means that a relatively long time is required to reach the threshold point. This is because the energy density within the discharge column decreases as the pulse duration increases and a large peak current requires relatively long pulse duration to attain the threshold. Fig. 9 shows the effect of machining polarity on surface roughness for the hybrid EDMUVAMF process. These experimental results show that the surface roughness for positive polarity machining was larger than that for negative polarity machining. Positive polarity created obvious material removal effects on the machined surface and produced relatively large and deep craters on the workpiece surface. Consequently, the machined surface had a large SR value for positive polarity machining. Fig. 10 shows the SEM micrographs for different discharge energies. The morphology of the machined surface demonstrated obvious discharge craters that depended on the discharge energy. Generally, the large and deep discharge craters generated on the machined surface would cause deteriorated surface integrity. These large and deep craters formed on the machined surface also produced surface defects, such as micro cracks, which hinder the efficient use of components.

4. Conclusions

This study determines the benefits and effects of the machining parameters for a newly developed hybrid EDMUVAMF process for SKD 61 tool steels. The experimental results and analyses allow the following conclusions to be drawn:

The developed hybrid EDMUVAMF process resulted in a greater MRR and a finer surface integrity, and it was potentially applicable to the machining of large areas. The hybrid EDMUVAMF process facilitated the evacuation of debris from the machining gap by ultrasonic vibration and magnetic driving force. Thus, the developed hybrid process produced an obvious improvement in machining performance.

The MRR for the hybrid EDMUVAMF process increases as the peak current was increased. The MRR also initially increased as the pulse duration increases. A further increase in the pulse duration after the peak value resulted in a reduction in the MRR. In addition, the positive polarity machining could obtain higher MRR.

The EWR for the hybrid EDMUVAMF process was increased when the peak current was increased, and it reduced when the pulse duration is increased. In addition, positive polarity machining produced a greater EWR and negative polarity machining resulted in an extremely low EWR.

The SR for the hybrid EDMUVAMF process increased as the peak current was increased. The initial increase of SR followed that the pulse duration was increased until it reached a peak value. The SR decreased afterwards. In addition, a higher SR was resulted in positive polarity machining than it does in negative polarity machining.

ACKNOWLEDGEMENT

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC 99-2221-E-252-006-MY3 and NSC-98-2221-E-252-010.

REFERENCES

1. Luis, C. J., Puertas, I., and Villa, G., "Material Removal Rate and Electrode Wear Study on the EDM of Silicon Carbide," Journal of Materials Processing Technology, Vol. 164-165, pp. 889-896, 2005.

2. Lin, Y. C., Chen, Y. F., Lin, C. T., and Tzeng, H. J., "Electrical Discharge Machining (EDM) Characteristics associated with Electrical Discharge Energy on Machining of Cemented Tungsten Carbide," Materials and Manufacturing Processes, Vol. 23, No. 4, pp. 391-399, 2008.

3. Yadav, R. N. and Yadava, V., "Experimental Study of Erosion and Abrasion based Hybrid Machining of Hybrid Metal Matrix Composite," Int. J. Precis. Eng. Manuf., Vol .14, No. 8, pp. 1293-1299, 2013.

4. Sanchez, J. A., Cabanes, I., Lopez de Lacalle, L. N., and Lamikiz, A., "Development of Optimum Electrodischarge Machining Technology for Advanced Ceramics," International Journal of Advanced Manufacturing Technology, Vol. 18, No. 12, pp. 897-905, 2001.

5. Fukuzawa, Y., Mohri, N., Tani, T., and Muttamara, A., "Electrical Discharge Machining Properties of Noble Crystals," Journal of Materials Processing Technology, Vol. 149, No. 1-3, pp. 393-397, 2004.

6. Puertas, I. and Luis, C. J., "A Study of Optimization of Machining Parameters for Electrical Discharge Machining of Boron Carbide," Materials and Manufacturing Processes, Vol. 19, No. 6, pp. 1041-1070, 2004.

7. Lin, Y. C., Cheng, C. H., Su, P. L., and Hwang, L. R. "Machining Characteristics and Optimization of Machining Parameters of SKH 57 High-Speed Steel Using Electrical-Discharge Machining Based on Taguchi Method," Materials and Manufacturing Processes, Vol. 21, No. 8, pp. 922-929, 2006.

8. Tzeng, C. J. and Chen, R. Y., "Optimization of Electric Discharge Machining Process using the Response Surface Methodology and Genetic Algorithm Approach," Int. J. Precis. Eng. Manuf., Vol. 14, No. 5, pp. 709-717, 2013.

9. Kuo, C. L. and Huang, J. D., "Fabrication of Series-Pattern Micro-Disk Electrode and its Application in Machining Micro-Slit of less than 10 mm," International Journal of Machine Tools & Manufacture, Vol. 44, pp. 545-553, 2004.

10. Kunieda, M., Hayasaka, A., Yang, X. D., Sano, S., and Araie, I., "Study on Nano EDM using Capacity Coupled Pulse Generator," CIRP Annals-Manufacturing Technology, Vol. 56, No. 1, pp. 213-216, 2007.

11. Chung, D. K., Shin, H. S., Park, M. S., Kim, B. H., and Chu, C. N., "Recent Researches in Micro Electrical Machining," Int. J. Precis. Eng. Manuf., Vol. 12, No. 2, pp. 371-380, 2011.

12. Cao, X. D., Kim, B. H., and Chu, C. N., "Hybrid Micromachining of Glass using ECDM and Micro Grinding," Int. J. Precis. Eng. Manuf., Vol. 14, No. 1, pp. 5-10, 2013.

13. Lou, Y. F., "The Dependence of Interspace Discharge Transitivity upon the Gap Debris in Precision Electrodischarge Machining," Journal of Materials Processing Technology, Vol. 68, No. 2, pp. 121-131, 1997.

14. Certin, S., Okada, A., and Uno, Y., "Effect of Debris Accumulation on Machining Speed in EDM," International Journal of Electrical Machinig, No. 9, pp. 9-14, 2004.

15. Kremer, D., Lhiaubet, C., and Moisan, A., "A Study of the Effect of

Synchronizing Ultrasonic Vibrations with Pulses in EDM," CIRP Annals-Manufacturing Technology, Vol. 40, No. 1, pp. 211-214, 1991.

16. Lin, Y. C., Yan, B. H., and Chang, Y. S., "Machining Characteristics of Titanium Alloy (Ti-6Al-4V) using Combination Process of EDM with USM," Journal of Materials Processing Technology, Vol. 104, No. 3, pp. 171-177, 2000.

17. Zhang, Q. H., Zhang, J. H., Deng, J. X., Qin, Y., and Niu, Z. W., "Ultrasonic Vibration Electrical Discharge Machining in Gas," Journal of Materials Processing Technology, Vol. 129, No. 1-3, pp. 135-138, 2002.