ELECTRICAL DISCHARGE DRILLING OF METAL MATRIX COMPOSITES WITH A HOLLOW HEXAGONAL ELECTRODE

Zhibiao Lin, Zhongning Guo, Shuzhen Jiang, Guixian Liu, Jiangwen Liu*

School of Electromechanical Engineering, the Guangzhou Key Laboratory of Nontraditional Machining and Equipment, Guangdong University of Technology, Guangzhou 510006, PR China

*Author to whom correspondence should be addressed: E-mail: j.w.liu@126.com

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ABSTRACT

Aimed at the problems of the conventional electrical discharge machining of particle-reinforced aluminum matrix composites (PR-AMCs),a novel hollow hexagonal electrode has been employed and the influence of the electrode structure on the MRR has been investigated. In this study, 3-D model of the working medium fluid flow field has been established to study the structure effect of the hexagonal electrode.And a lot of single factor comparison experiments are carried out between the hexagonal hollow electrode and round hollow electrode. The effects of peak current, duty cycle, machining rotation speed and pulse width on the MRR of work-piece has been studied respectively. The Response Surface Method (RSM) is adopted to imitate the law of machining surface of the hexagonal hollow electrode. The theoretical and experimental resultsboth show that the MRR of the work-piece can be improved remarkably by using a hexagonal hollow electrode. Moreover, according to the RSM, the maximum MRR of machining AMCs of the hexagonal hollow electrode is 225mm^3/min, while the optimum combination of parameters that the peak current (12A), the duty cycle (0.75), machining rotation speed (900 r/min) and flushing pressure (1.5MPa) is exerted.

Key words:Particle-reinforced; aluminum matrix composites; Electrical discharge machining; Flow field simulation; Hexagonal hollow electrode; MRR; Response surface

1. INTRODUCTION

Particle-reinforced aluminum matrix composites (PR-AMCs), based on aluminum matrix and ceramic particles reinforced, have been increasingly applied in the automotive, defense, aerospace and aircraft industries[1] because of their high specific strength, higher Young's modules, and good stiffness, low thermal expansion and good thermal stability, isotropic properties and wear resistance[2-7],which prospects is extremely broad, such as automobile pistons, cylinder liners, piston ring, connecting rods, sliding electrical contacts, turbo charger impellers, space structures, and so on[8]. Although it has lots of advantages, particle-reinforced aluminum matrix composites(AMCs) are a material that is extremely hard to produce at the same time, especially the machining becomes more difficult with the reinforced phase volume fraction and particle size increases, which has been become a barrier to limit its further application. Currently, mechanical cutting, a traditional methods of processing AMCs, has a significant drawback, for instance, the main problem while processing AMCs is the excessive tool wear caused by the vary hard and abrasive reinforcements as well as higher costs, lower quality and lower efficiency and so on[9].Due to the shortcomings above-mentioned, it becomes more and more popular for people to apply special processing method of processing ACMs, such as electrical discharge machining processing methods, laser processing methods, water jet processing methods, electrochemical machining processing methods and so on.However,each of them has its own drawback,for example,laser processing will lead to the formation of aluminum carbide structure,which will not only damage mechanical properties of workpiece,but also create heat damage on the edge of the work piece[10,11]. Water jet processing obtain poor cutting precision and unstable cutting surface quality[12].It is difficult to control the precision of electrochemical machining,besides,the efficiency of particle aluminum matrix composite processing is not high[13].

Among these non-conventional manufacturing methods,electric discharge machining(EDM) is considered to be one of the most suitable ways for processing AMCs[14],EDM machining is non-contact machining without generating mechanical stress,the hardness, intension, roughness of ACMs have no effect on the materials removal rate(MRR),therefore,it

can effectively avoid workpiece crack when cutting the workpiece, moreover,it can obtain a good dimensional accuracy. Although it has such an advantages, there is still many problems need to be solved, these problems are mainly caused by the ceramics particle of the AMCs.Ceramics particle is a kind of insulating materials,and its melting point is higher than aluminum matrix, thus, the aluminum matrix will be removed first during the course of processing,and then the ceramics particle will be drown out, hence, the ceramics particle has a negative effect on MRR,moreover,the electrical conductivity and thermal conductivity will be decreased with the increase of the ceramics particle volume fraction, which will cause the lower MRR[15].Besides,the efficiency of processing MRR will be reduced with the increasing depth of machining,and the removal of particle can cause the secondary discharge,which will result in the unstable course of processing, unfortunately,the effect will get more apparently with the raising of depth to diameter ratio[16].

Many scholars study on main factors influence on MRR in EDM,they pay more attention on how to improve the efficiency of machining by optimizing parameters,they have found out that the greater the current and duty cycle,the higher MRR will be obtained as well as the worse surface roughness[15,17]. B Mohan[15] has improved the MRR and reduced the electrode wear as well as improved the surface roughness by adding trough in the circle of the electrode for EDM machining.

In this paper,a hexagonal hollow tool electrode has been designed to improve the machining efficiency in the EDM of MRR, the influences of each sides are similar to the hole in the circle of the electrode,from the perspective of chip removal,the machined debris will spread to the edge of the bottom of electrode in flush fluid pressure and rotating centrifugal force,it is more easily to discharge the debris between the hexagonal hollow electrode and the workpiece because of the enlarged gap, and then start the single factor experiment coMPared to round electrode separately to find out which one is the highest efficiency. Furthermore, the Response Surface Method (RSM) has been used for optimizing the processing parameters of the EDM machining in this study.

2. THE PRINCIPLE OF THE EDM MACHINING OF PARTICLE-REINFORCED ALUMINUM MATRIX COMPOSITES WITH A HEXAGONAL HOLLOW ELECTRODE

The schematic diagram of the EDM machining of PRAMCs with ahexagonal hollow electrode is shown in Fig.1 and Fig.2.

The EDM process consists of several of processes, which generally seen as: liquid ionization, breakdown,plasma channel formed, thermal decomposition of working fluid, melting of electrode materials, gasification of thermal expansion and debris removal. It is a critical step to discharge the debris from the spark gap, which plays an important role in MRR. When a round electrode is used for EDM machining, it is clear that the gap between the spark area is too narrow and small (see Fig.2(a)),which has a limitation on MRR, especially with the increase of pulse width and current, this influence would be more apparently owing to the debris would be much bigger, besides, because the shape of electrode is round, it results in the weak stirring force to working solution even though the electrode is rotating,which leads to the lower MRR.

Fortunately,once a hexagonal electrode is employed in the EDM process,the gap distance between the spark area is obviously enlarged(see Fig.2(b),which is more likely to drain out the debris from the spark

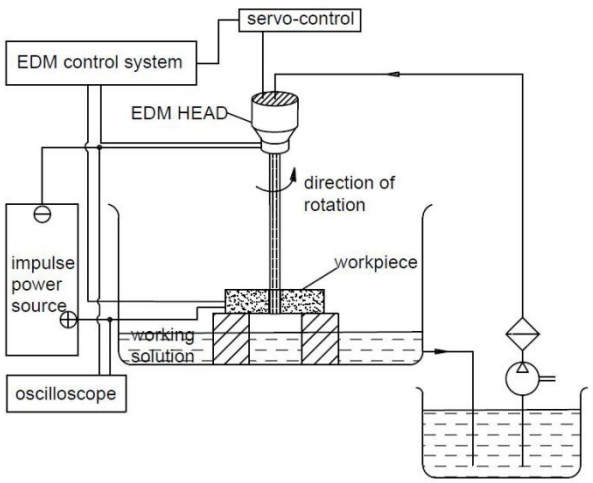

Fig. 1: Electrical discharge machining system schematic diagram

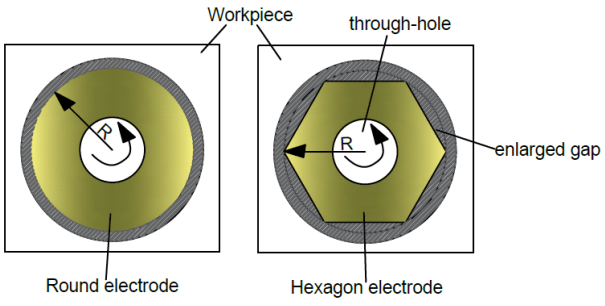

Fig.2: The gap situation of round electrode and hexagonal electrode.

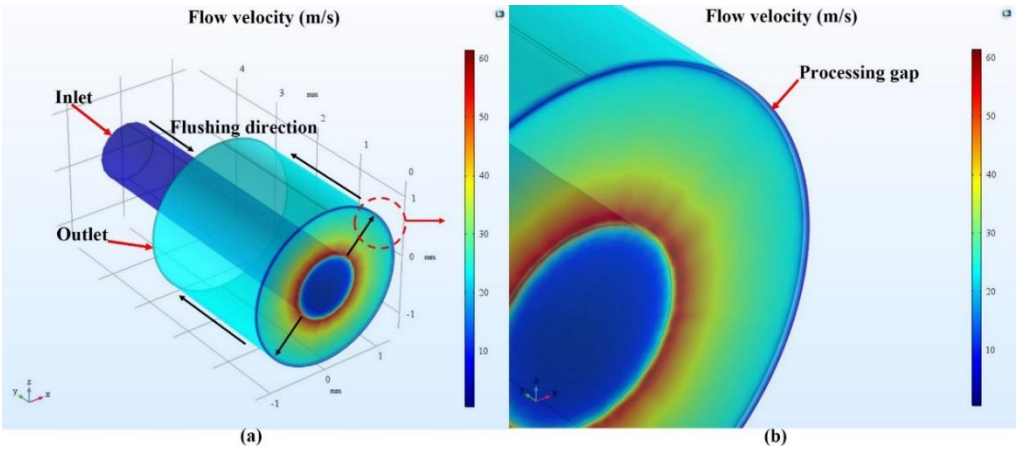

Fig. 3: Round electrode machining gap flow field simulation diagram

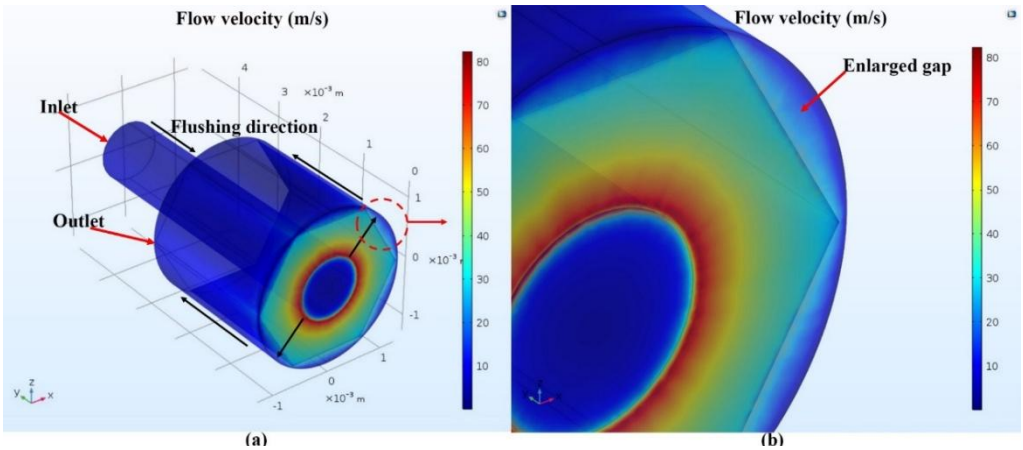

Fig. 4: Hexagonal electrode machining gap flow field simulation diagram

area, what's more, a hexagonal electrode would generate relatively big stirring force to working solution with the rotating of the hexagonal hollow electrode, and thus, a much higher MRR can be achieved.

3. FLOW FIELD SIMULATION FOR EDM OF THE TWO TYPES OF ELECTRODE MACHINING GAP

In the process of the EDM, the shape of the electrode plays an important role in determining the type of the flow field,in this study, two types of flow field model have been designed, it is shown in Fig.3(a) and Fig. 4(a). To verify the structure of the hexagonal electrode can facilitate the transportation of the working medium and the removal of machining debris, a flow field simulation has been carried out.The flow field geometry model parameter conditions are set as follows: the through hole radius is 1mm; the discharge gap between the bottom of the electrode and the workpiece is 20 μm; the gap between the electrode side and the workpiece is 18 μm. The boundary conditions are set as follows: the inlet pressure of working medium is set to 4 MPa, and outlet pressure is set to atmospheric pressure. Both the flow field simulation of the hexagonal electrode and round electrode is simulated by the COMSOL 5.3a software. To simplify the simulation model,several assumptions have been made: (1) The working medium fluid is continuous and incompressible; (2) Ignoring the change in temperature and energy of medium due to the temperature difference; (3) Ignoring the effect of convection as well as radiation.

In this simulation, the standard steady state k-ε model is applied in solving for the 3-D model of the working medium fluid flow field, which can be solved the momentum conservation of the Navier-Stokes equation and the conservation of mass continuity equation. The turbulence effect is modeled by a standard two-equation k-ε model with implementable constraints. Near-wall flow is modeled using wall functions.

Fig.3(a) and Fig.4(a) indicates the gap flow field of a round electrode and a hexagonal electrode in the process of EDM, respectively. the fluid direction is shown by the arrows in Fig. 3(a) and Fig. 4(b). The simulation results show that whether it is a round

electrode or a hexagonal electrode,the maximum fluid velocity occurs at the bottom of the spark gap, what's more, the maximum fluid velocity of the hexagonal electrode is bigger than that of the round electrode, which indirectly shows that the discharge debris gap of the hexagonal electrode is larger than that of the round electrode, because the larger the gap, the fluid flows more easily. The discharge debris gap of the round electrode and the hexagonal electrode is shown in Fig. 3(a) and Fig. 4(b), it clearly indicates that the discharge debris gap of the hexagonal electrode is much larger than that of the round electrode.

4. EXPERIMENTAL APPROACH

The actual machining diagram of the equipment is shown in Fig.5. The aluminum matrix composites used for the experiments were the particle reinforced aluminum alloy 6061 with 20vol% Al_2O_3,the average diameter of particle reinforced was 21μm, and the thickness of workpiece was 5mm. The deionized water was used as the working fluid,whose way of flushing electrolyte was the way to flush oil. Round tool electrode and regular pentagon electrode are made of through-hole brass electrode,on the one hand,outside diameter of the former and the letter were the same, which was taken as 2.5mm,on the other hand,the bore diameter of the former and the letter were the same too,which was taken as 1mm. Experimental equipment was a modified DD703 type EDM puncher,which was produced by SUZHOU CHANGFENG MECHATRONICAL SCIENCE AND TECHNOLOGY CO.,LTD.The adjustable spindle speed ranges from 0 to 2000 rpm. Furthermore, in this paper,a single factor test and Response Surface Method were used to analyze the results of the EDM machining parameter influences on the MRR with a regular pentagon electrode,among the Response Surface Method experiment,the current,duty cycle,spindle speed,pressure were selected as factors,each factor has five levels.

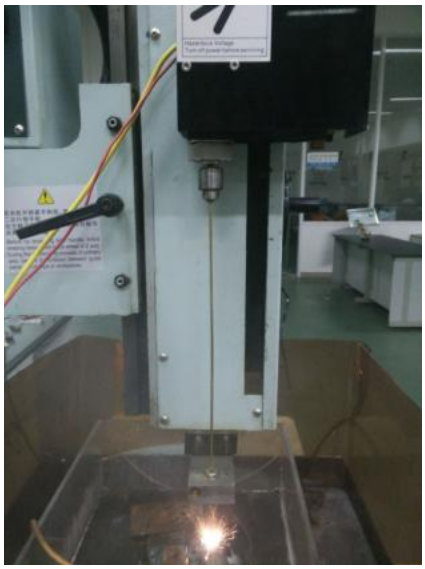

Fig.5: Actual machining diagram

5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Single-factor experiment

Firstly,round tool electrode and regular pentagon electrode were applied for machining the workpiece respectively,running a single factor test,and then,a result of observations was based on the machining efficiency,changed the peak current,spindle rotating speed,pulse duration,duty cycle successively in order to coMPare the MRR between the round electrode and regular pentagon electrode.In the course of the experiment,round electrode and regular electrode were used for drilling the workpiece of MMCs in EDM respectively.In order to reduce accidental error,the experiment was repeated five times in each group,and then calculated mean value,and finally, converted it into MRR.

Fig.6 shows the iMPact of peak current on MRR. During the machining,the voltage,duty cycle,pulse duration,rotary speed,flushing pressure were set to 95v,0.75,24us,800r/min,4MPa respectively,and the peak current varied from 4A to 16A.It indicates that the peak current has a great influence on both MRR of the round electrode and hexagonal electrode,the machining efficiency of hexagonal electrode is higher than what the round electrode is in a given condition,and for both the hexagonal electrode and the round electrode,the MRR improved strikingly with the increasing of the peak current,both of whom present an increasing trend with a linear trend of change.The MRR range from 25mm3/min to 235mm3/min with the increasing of the peak current from 4A to 16A.When the current was small,there was no significant differences of MRR between hexagonal electrode and round electrode,but when the current arrived 16A,the MRR of hexagonal electrode was too much larger than the MRR of round electrode. For the reason that the EDM spark energy was enlarged with the increasing of the current so that the quantities and size of debris removal increased per unit time,and the gap between hexagonal electrode and the workpiece was larger than it of the round electrode and the workpiece,which is shown in Fig.2,when the current is small,the EDM spark energy is also small,so the quantities and size of debris removal are very small,that's account for why there was no significant differences of MRR be-

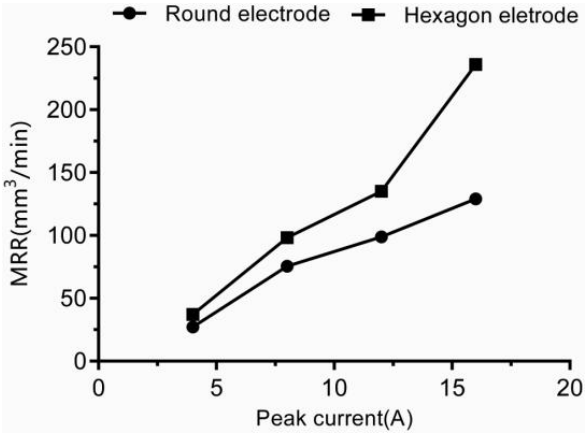

Fig.6: Influence of peak current on MRR

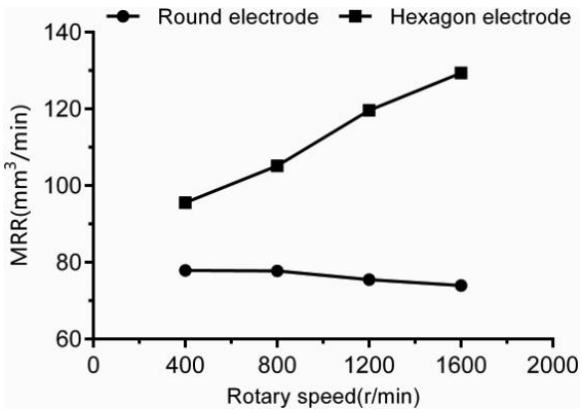

Fig.7: The influence of the rotary speed on the MRR

tween hexagonal electrode and round electrode in a situation of lower current,however, with the increasing of the current,both the quantities and size of the debris removal are increasing,at this moment,the enlarged gap means that a much higher MRR could be realized,that's why the curve of hexagonal electrode is steeper than the curve of round electrode in a situation of higher current which is shown in Fig.6.

The remove quantity can be expressed by the following equation(1):

$$q=\kappa\omega m f\Phi t \quad (1)$$

Where q is the remove quantity, $W_m$mis the energy of a single pulse;fis impulse frequency; K is a technological parameter that has related to electrode material; pulse parameter and work solution;ϕ is the effective utilization rate of pulse.

The energy of a single pulse can be expressed by the following equation(2):

$$W_m = \int_0^{t_e} u(t)i(t)dt \quad (2)$$

Where t_e is the EDM spark maintain time;u(t) is the voltage between tool electrode and the workpiece; i(t) is the current between tool electrode and workpiece.It could easily be found in the above equation that the greater the current (i(t)) would get,the larger the W_m would be when other things remain equal,however,on the other hand,the surface roughness would get worse.

Fig.7 shows the iMPact of rotary speed on the MRR,during the machining, the voltage,duty cycle, pulse duration, peak current,flushing pressure were fixed at 95v,0.75,24us,8A ,4MPa respectively,and the rotary speed varied from 400r/min to 1600r/min. It has been found that the efficiency of hexagonal electrode is higher than the efficiency of round electrode in the scope of a given condition,the mean of MRR of hexagonal electrode is approximately 45% more than it of the round electrode.The variation tendency on MRR of hexagonal electrode was significant, while the variation tendency on MRR of round electrode was keep flat.First of all,the gap distance between the hexagonal electrode and the workpiece is bigger than that of the round electrode which results in a better debris removal condition,thus,a higher MRR can be obtained.Secondly, a hexagonal electrode would generate relatively big stirring force to working solution with the rotating of the hexagonal electrode,so,a higher MRR can be achieved,which accounts for why the curve of hexagonal electrode is steeper than the curve of round electrode. Test study indicates that high efficiency can be achieved in high rotary speed machining.

Fig.8 shows the influence of the duty cycle on the MRR of the hexagonal electrode and round electrode. During the processing, he voltage, pulse duration intervals, peak current, rotary speed, flushing pressure were fixed at 95v,8us,8A,800r/min,4MPa respectively, and the duty cycle varied from 0.67 to 0.87. It has been found that the MRR of hexagonal electrode is higher than the MRR of round electrode in the scope of a given condition,the mean of MRR of hexagonal electrode is approximately 30% more than it of the round electrode. When the duty cycle was small,such as between 0.67 and 0.75,the MRR of both of them had a same variation tendency that was a significantly increasing MRR,for the reason that the larger duty cycle means more EDM pulse power during single pulse period.When the duty cycle increased from 0.75 to 0.87,the MRR of the hexagonal electrode and the round electrode was still increasing,but the MRR of increasing speed is reduced,which means duty cycle is not the bigger the bigger.

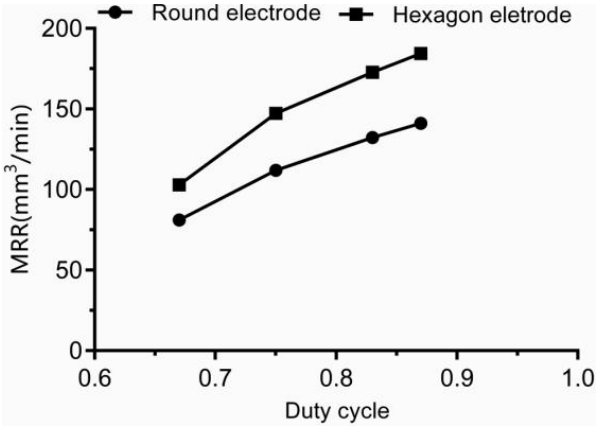

Fig.8: The influence of duty cycle on the MRR.

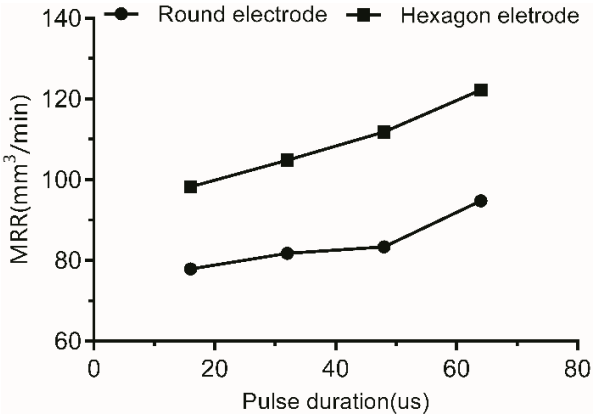

Fig.9: The influence of pulse duration on the MRR.

Fig.9 shows the influence of pulse duration on the MRR of hexagonal electrode and the round electrode.During the processing, the voltage, duty cycle,peak current,rotary speed, flushing pressure were fixed at 95v,0.75,8A,800A,4MPa respectively, and the pulse duration varied from 16us to 64us. It has been found that the MRR of hexagonal electrode is higher than the MRR of round electrode in the scope of a given condition,the mean of MRR of hexagonal electrode is approximately 29.8% more than it of the round electrode.Both of them has the same variation tendency with the increasing of the pulse duration.Both hexagonal electrode and round electrode got the maximum value when the pulse duration is 64us and got the minimum value when the pulse duration is 16us,that was because that the larger the pulse duration was,the larger the single pulse energy would be,thus,the MRR of both of them would be higher,besides,the gap between the hexagonal electrode and the workpiece is larger than the gap between the round electrode and the workpiece, therefore, a much higher MRR can be obtained.

5.2 Response Surface Methodology to optimize the MRR of machining parameters.

5.2.1 The establishment of the model.

The parameters of the MRR processing condition are optimized by using the composite design principle of the response surface methodology. In the experiment, the current,duty cycle, the spindle rotary speed and the flushing pressare selected as four factors,each factor has five levels. It is shown in Table 1.The MRR of hexagonal electrode is selected as the results of the experimental response.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \varepsilon \quad (3)$$

χ_i is the independent input variables,β_0,β_i,β_{ii},β_{ij} is the second order regression factor.In the polynomial equation,$\sum^{\kappa}_{i=1} \beta_i \chi_i$ represent the linear relation expression and $\sum^{\kappa}_{i=1} \beta_{ii} \chi^2_i$ indicate the quadratic relation,$\sum^{\kappa}_{i<j} \beta_{ij} \chi_i \chi_j$ represent the interaction of factors and ε is fitting error.

5.2.2 Model variance analysis.

According to the factors and the response values,the Design-Expert 8.05b generates 30 sets of test points. It is shown in Table 2. The data are subjected to multiple quadratic response surface fitting by Design-Expert 8.05b,and obtained the following quadratic regression equation model of MRR:

$$Y=130.32+42.99x_1+3.08x_2+8.32x_3-17.8x_4-2.71x_1x_2+8.81x_1x_3-18.5x_1x_4+2.91x_2x_3+2.73x_2x_4+1.9\,3x^2_1-6.45x^2_2+5.06x^2_3+3.38x^2_4 \quad (4)$$

In the equation,Y is the MRR;x_1 is the peak current;

Table 1: Factors and levels of the response surface methodology experiment

factor	mark	level				
		-2	-1	0	+1	+2
Peak current (A)	X_1	6	9	12	15	18
Duty cycle	X_2	0.67	0.71	0.75	0.79	0.83
n(r/min)	X_3	0	400	800	1200	1600
P(kg/cm^2)	X_4	0	0.25	0.50	0.75	1

Table 2: Design of experiments

	A:peak current/A	B:duty cycle	C:rotary speed/r/min	D:flushing pressure/Mpa	MRR/ mm^3/m
1	9	0.75	600	0	160
2	9	0.75	600	3	111
3	12	0.71	300	4.5	92
4	12	0.79	300	4.5	103
5	12	0.71	900	1.5	206
6	9	0.75	600	3	145
7	9	0.67	600	3	101
8	3	0.75	600	3	43
9	12	0.79	900	1.5	232
10	6	0.71	300	1.5	92
11	9	0.75	600	6	119
12	12	0.71	300	1.5	235
13	6	0.71	900	1.5	91
14	6	0.79	900	4.5	105
15	6	0.71	900	4.5	94
16	6	0.79	300	4.5	95
17	9	0.75	0	3	143
18	12	0.71	900	4.5	170
19	9	0.75	600	3	144
20	6	0.79	300	1.5	108
21	9	0.75	600	3	144
22	6	0.71	300	4.5	72
23	12	0.79	900	4.5	185
24	6	0.79	900	1.5	100
25	9	0.75	600	3	119
26	9	0.83	600	3	100
27	9	0.75	600	3	119
28	15	0.75	600	3	226
29	12	0.79	300	1.5	200
30	9	0.75	1200	3	150

x_2 is the duty cycle; x_3 is the spindle rotary speed; x_4 is the flushing pressure. The result of variance analysis of MRR is shown in Table 3. Since $P<0.0001$, it indicates that regression equation model is highly significant.Factor x_1 and x_4 has a highly significant effect on MRR,factor x_3 has a significant influence on MRR and x_2 has a little significant effect on MRR.According to the size of F values,the bigger the F values is, the more significant it will be on MRR,thus,factor significant in ascending order is $x_1>x_4>x_1$ $x_4>x_3>x_2$.

5.2.3 Model reliability analysis

The Fig.10(a) is the normal probability distribution of the MRR for EDM machining by hexagonal electrode,the points in the figure are closer to a slash, which indicates that the fit is better.Furthermore,the Fig.10(b) is the reliability analysis of quadratic regression equation of the MRR for EDM machining by hexagonal electrode,the actual experimental values are closer to a slash,which represents that the predicted model and experiment fit well,thus,this model is feasibleFurthermore,the R-squared of quadratic regression equation of the MRR for EDM machining by hexagonal electrode is 0.9348, and the Adj R-squared is 0.8740,which further verify the

Table 3:Model variance analysis

Source	Sum of squares	df	Mean square	F Value	P Value Prob>F	
Model	65938.48	14	4709.89	15.37	<0.0001	significant
x_1	44356.22	1	44356.22	144.78	<0.0001	
x_2	227.12	1	227.12	0.74	0.4028	
x_3	1663.17	1	1663.17	5.43	0.0342	
x_4	7605.23	1	7605.23	24.82	0.0002	
x_1x_2	117.45	1	117.45	0.38	0.5451	
x_1x_3	1242.39	1	1242.39	4.06	0.0623	
x_1x_4	5476.37	1	5476.37	17.87	0.0007	
x_2x_3	135.78	1	135.78	0.44	0.5157	
x_2x_4	119.08	1	119.08	0.39	0.5424	
x_3x_4	2406.64	1	2406.64	7.86	0.0134	
x_1^2	102.27	1	102.27	0.33	0.5720	
x_2^2	1141.65	1	1141.65	3.37	0.0727	
x_3^2	703.57	1	703.57	2.30	0.1505	
x_4^2	313.99	1	313.99	1.02	0.3273	
Residual	4595.68	15	306.38			
Lack of Fit	3348.33	10	334.83	1.34	0.3924	Not significant
Pure Error	1247.35	5	249.47			
Cor total	70534.16	29				

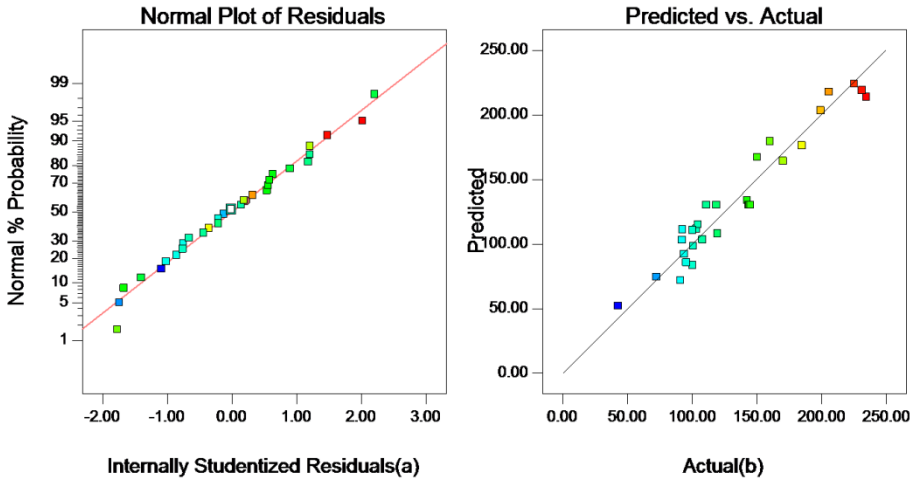

Fig. 10: Model reliability analysis diagram

accuracy of the model.

5.2.4 Factor interaction

The figure for the effect of the factor interaction on MRR are shown as following Fig.11(a-c).The Fig.11(a) show us that the MRR increases significantly with the current increasing,while the MRR increase first and then decrease with the increasing of the duty cycle,which indicates that the increase in current will suppress the effect of duty cycle on MRR.The Fig.11(b) shows us that the MRR increase slowly with the increasing of the rotary speed,what's more,it indicates that the current and the rotary

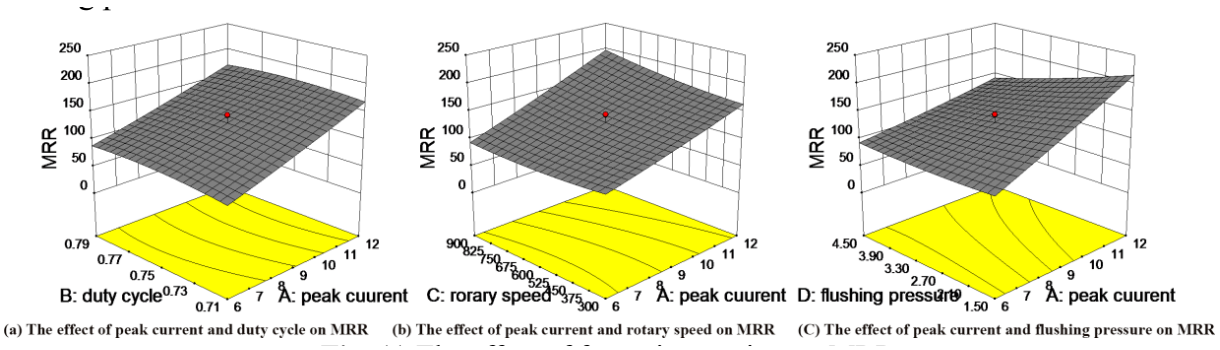

Fig. 11: The effect of factor interaction on MRR

speed to promote each other.Fig.11(c) show us that the MRR decrease slowly with the increasing of the flushing pressure.

5.2.5 Best optimization parameter condition

Optimized analysis by Design Expert 8.0.5b,the best optimization parameter condition: peak current is 12A;duty cycle is 0.75; rotary speed is 900r/min and flushing pressure is 1.5 MPa;the best optimization MRR is 225 mm3/min.

5.3 Debris analysis

Fig.12 shows the debris SEM graph collected from the round electrode and the hexagonal electrode respectively during the EDM process.The process condition is to process five holes.During the process, the voltage,duty cycle,pulse duration, rotary speed, flushing pressure are fixed at 95v, 0.75, 24us, 800 r/min, 4 MPa respectively. MASTERSIZER 2000 has been used to measure the debris size and analyze the particle size distribution.It was found that the debris volume average diameter collected from the round electrode for EDM process was 23.5μm,while the debris volume average diameter for the hexagonal electrode was 29.8μm. Because the gap distance could be apparently enlarged with a hexagonal electrode,that's why the volume average diameter for the hexagonal electrode is bigger than the volume average diameter for the round electrode.What's more, Fig.13 shows us that both of them have a sim-

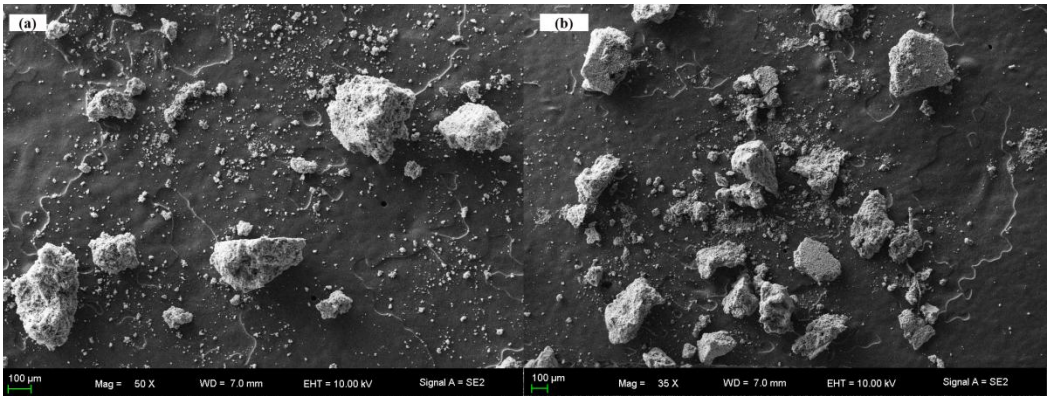

Fig.12: The collected debris from the round electrode process(a) and hexagonal electrode process (b)

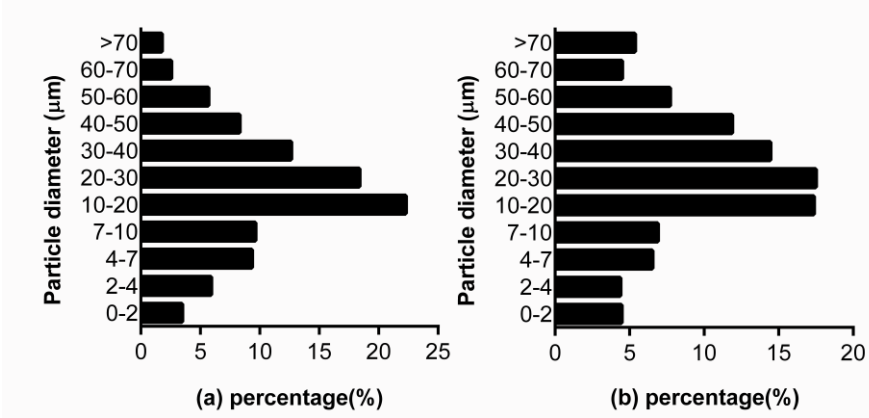

Fig.13:Particle size distribution: round electrode(a) and hexagonal electrode (b)

ilar regular pattern of particle size distribution,most of the particle size of debris are concentrated in between 10μm and 50μm,however,the particle size of debris above 50μm during the EDM of AMCs process with a hexagonal electrode was bigger than the round electrode, it indicates that more and larger debris could be discharged out of the machining process with a hexagonal electrode,which accounts for the reason that why the MRR of the hexagonal electrode is bigger than the MRR of the round electrode.

6. CONCLUSIONS

An EDM machining with hexagonal through hole electrode has been designed to improve the MRR for machining particle reinforced MMCs in this paper.And the mainly conclusions obtained are as following:

1.The flow field simulation shows that the maximum fluid velocity of the hexagonal electrode is bigger than that of the round electrode, which indirectly shows that the discharge debris gap of the hexagonal electrode is larger than that of the round electrode, because the larger the gap, the fluid flows more easily.

2.The processing efficiency of EDM with hexagonal through-hole electrode is significantly higher than that of the round electrode in the scope of a given condition.

3.The model of multiple quadratic regression equation created by applying the Design Expert 8.0.5b and using the composite design principle of the response surface methodology indicates that the rank of significance for four factors is peak current>flushing pressure>spindle rotary speed>duty cycle.The interaction between peak current and flushing pressure has a significantly effect on the MRR.

4.The best optimization parameter condition:the peak current is 12A;the duty cycle is 0.75;the rotary speed is 900 r/min;the flushing pressure is 1.5 MPa;the best optimization MRR is 224.85 mm3/min.

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References:

1. Chen, Z., et al., Multi-scale study of microstructure evolution in hot extruded nano-sized TiB2 particle reinforced aluminum composites. Materials & Design, 2017. 116: p. 577-590.
2. Giugliano, D., D. Barbera, and H. Chen, Effect of fiber cross section geometry on cyclic plastic behavior of continuous fiber reinforced aluminum matrix composites. European Journal of Mechanics - A/Solids, 2017. 61: p. 35-46.
3. Hu, Q., H. Zhao, and F. Li, Microstructures and properties of SiC particles reinforced aluminum-matrix composites fabricated by vacuum-assisted high pressure die casting. Materials Science and Engineering: A, 2017. 680: p. 270-277.
4. Li, G.R., et al., The influence of cryogenic-aging circular treatment on the microstructure and properties of aluminum matrix composites. Journal of Alloys and Compounds, 2017. 695: p. 1930-1945.
5. Li, S., et al., Enhanced mechanical behavior and fabrication of silicon carbide particles covered by in-situ carbon nanotube reinforced 6061 aluminum matrix composites. Materials & Design, 2016. 107: p. 130-138.
6. Raei, M., M. Panjepour, and M. Meratian, Pseudo-in-situ stir casting: a new method for production of aluminum matrix composites with bimodal-sized B4C reinforcement. International Journal of Minerals, Metallurgy, and Materials, 2016. 23(8): p. 981-990.
7. Wang, X., et al., A new approach for preparing SiC particle-reinforced aluminum matrix composites by applying electromagnetic field. Journal of Wuhan University of Technology-Mater. Sci. Ed., 2016. 31(4): p. 717-721
8. Seeman, M., et al., Study on tool wear and surface roughness in machining of particulate aluminum metal matrix composite-response surface methodology approach. The International Journal of Advanced Manufacturing Technology, 2009. 48(5-8): p. 613-624.
9. Ding, X., W.Y.H. Liew, and X.D. Liu, Evaluation of machining performance of MMC with PCBN and PCD tools. Wear, 2005. 259(7-12): p. 1225-1234.
10. Dandekar, C.R. and Y.C. Shin, Multi-scale modeling to predict sub-surface damage applied to laser-assisted machining of a particulate reinforced metal matrix composite. Journal of Materials Processing Technology, 2013. 213(2): p. 153-160.
11. Zhou, Y.C., S.G. Long, and Y.W. Liu, Thermal failure mechanism and failure threshold of SiC particle reinforced metal matrix composites induced by laser beam. Mechanics of Materials, 2003. 35(10): p. 1003-1020.
12. Löschner, P., K. Jarosz, and P. Niesłony, Investigation of the Effect of Cutting Speed on Surface Quality in Abrasive Water Jet Cutting of 316L Stainless Steel. Procedia Engineering, 2016. 149: p. 276-282.
13. Pramanik, A., Developments in the non-traditional machining of particle reinforced metal matrix com-

posites. International Journal of Machine Tools and Manufacture, 2014. 86: p. 44-61.

14. Garg, R.K., et al., Review of research work in sinking EDM and WEDM on metal matrix composite materials. The International Journal of Advanced Manufacturing Technology, 2010. 50(5-8): p. 611-624
15. Mohan, B., A. Rajadurai, and K.G. Satyanarayana, Electric discharge machining of Al–SiC metal matrix composites using rotary tube electrode. Journal of Materials Processing Technology, 2004. 153-154: p. 978-985.
16. Chen, R., et al., A numerical model and computer simulation for machining particle reinforced metal matrix composites in electric discharge machining. Materials Research Innovations, 2015. 19(sup1): p. S1-392-S1-396.
17. Singh, P.N., et al., Electric discharge machining of Al–10%SiCP as-cast metal matrix composites. Journal of Materials Processing Technology, 2004. 155-156: p. 1653-1657.