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Improving EDM Process on AZ31 Magnesium Alloy towards Sustainable Biodegradable Implant Manufacturing

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Abstract

The electrical discharge machining (EDM) process is an excellent method to machine with the high geometrical accuracy required for bio-medical implants. In implant fabrication, a higher surface roughness has led to a huge contact surface area which causes a higher corrosion rate. Uneven spark distribution in conventional EDM (C-EDM) has led to negative effects on the machined surface quality. Particles mixed-EDM (PM-EDM) was found promising to improve the quality of the machined surface. The objective of this paper is to improve the machined surface quality of AZ31 magnesium alloy using the PM-EDM method towards sustainability manufacturing of biodegradable implant. It was hypothesized that with the addition of zinc particles in the dielectric fluid, the roughness of the machining surface could be reduced. The Taguchi method was used with nine experiments on C-EDM and PM-EDM with an opened-loop system which were conducted with the same setting parameters. Different concentrations of the zinc particles were mixed in the dielectric fluid during the PM-EDM experiments. In both the C-EDM and PM-EDM experiments, the pulse on-time was found as the most significant parameter affecting the quality of the machined surface. However, the addition of the zinc particles in the PM-EDM experiments did end up with a positive effect on the machined surface quality. The optimized surface roughness obtained from the PM-EDM experiment had been reduced by 44% compared to C-EDM. The PM-EDM method has been proven to reduce the roughness of the machined surface. More research is required to determine the efficacy of the PM-EDM method in solving the high corrosion rate of the magnesium alloy.

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Keywords: Biodegradable material; EDM; magnesium alloy; surface roughness; zinc particles.

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1. Introduction

Magnesium and its alloys have been established as being compatible for biodegradable implants [1-4]. However, machining magnesium alloys using conventional methods, such as milling, turning, and drilling, causes a built-up edge and chatter. The most important precaution needed to bear in mind whilst machining magnesium alloy is that the formation of fine chips and dust are highly flammable [5]. The melting point of magnesium is 650°C, and this metal is only stable below its melting point. Non-traditional machining, such as the EDM process, is preferable to machine magnesium especially to machine the high geometrical accuracy required by bio-medical implants [6, 7]. In implant fabrication, higher surface roughness has led to a huge contact surface area which causes a higher corrosion rate. However, uneven spark distribution in the conventional EDM (C-EDM) has led to negative effects on the machined surface. Recently, new exploratory research works have been initiated to improve the efficiency of the EDM process using the PM-EDM method [8]. In PM-EDM, the added particles help to improve the sparking efficiency during the ignition process. It was found that the addition of conductive particles led to an increase in gap size which subsequently resulted in a reduction of the electrical discharge power density. The added conductive particles lowered the dielectric strength creating early and uniform electric discharges at low energy, improving the machined surface. In the PM-EDM process, the added particles can be suspended in the dielectric fluid in the same machining tank or a separate tank. The use of a stirrer and circulating pump was to ensure the uniform distribution of the conductive particles [9-14]. The objective of this paper was to improve the machined surface quality of the AZ31 magnesium alloy using the PM-EDM method towards sustainable manufacturing process of biodegradable implant. It was hypothesized that with the addition of the zinc particles in the dielectric fluid, the roughness of the machined surface could be reduced.

2. Literature review

Nanimina et al. [11] categorized the dielectric fluid circulation operating tank system used in the PM-EDM process into closed-loop and opened-loop. In closed-loop operating tank, stirrer, and circulating pump were used to ensure the uniform distribution of the added particles. However, the same dielectric fluid and debris would be compounded in the operating tank throughout the process. Meanwhile, the opened-loop operating tank was connected to an external reservoir to circulate the renewal dielectric fluid during the process. The stirrer and circulating pump were placed in the operating tank whilst a dielectric fluid filter was placed in the reservoir to filter the debris.

Most of the researchers reported the advantages of PM-EDM in improving the surface finish, reducing the material removal rate and tool wear rate, and the modification of the machined surface [15-18]. For example, Zain et al. [16] carried out the PM-EDM experiments using tantalum carbide particles on a stainless steel workpiece at various levels of peak current and particle concentrations. The particle concentration values used were 5 g/l, 10 g/l, and 15 g/l. They reported that the material removal rate and surface roughness were enhanced by increasing the current. Their report was lacking in information on the particle size although it gave significant effects on the machining efficiency. On the other hand, Ajay and Anirban [19] suggested that some of the removed materials got deposited on the machined surface. Pecas and Henriques [20] agreed that PM-EDM promotes the reduction of surface roughness and craters. With the spark frequency up to 10000 sparks per second and the spot temperature up to 20000°C during the process, not only were some materials removed from the workpiece, but also the added conductive particles existing in the dielectric fluid also melted and were deposited on the machined surface. This phenomenon caused a modification on the machined surface. The advantages of the PM-EDM method require deeper clarification in order to meet the needs of high precision industries, such as the bio-medical and aerospace industries.

3. Methodology

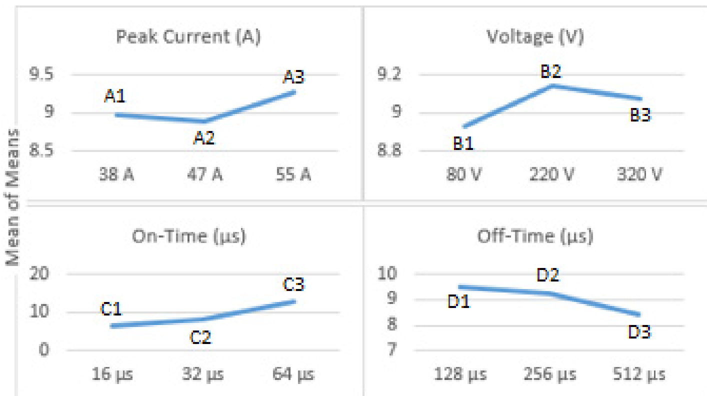
The workpiece material used in this research was AZ31 magnesium alloy and the tool electrode used was copper. A constant cutting depth of 2 mm was maintained throughout the experiments. The parameter values as suggested in the machine user manual were used in the experiments. The Mitutoyo SV3000 Surface Roughness Tester was used to measure the surface roughness at three different locations on each specimen. Nine C-EDM experiments were conducted with three levels and four parameters, which were the peak current, voltage, pulse on-time, and pulse off-time. The condition of each experiment can be found in the result and discussion section. Each experiment was repeated diligently three times to ensure data accuracy. The optimum C-EDM parameters for the smoothest surface were obtained using the Taguchi approach. The steps involved in the Taguchi method were used to determine the experimental parameters and to create the orthogonal arrays, conduct the experiments, analyze the data to determine the effect of each parameter, and predict the optimum parameters.

Then, nine PM-EDM experiments were conducted with the same setting for the three levels, four parameters, and three times of repetitions. The experiments were carried out using the opened-loop PM-EDM system with a separate machining tank which as equipped with a stirrer and external reservoir. Zinc particles with an average size of 80 nm in diameter with three different concentrations were mixed in the dielectric fluid. Zinc particles were used in the experiment due to the biocompatibility and they are one of the major components in AZ31 magnesium alloy. The obtained results from the PM-EDM experiments were analyzed and compared with C-EDM.

4. Result and discussion

Table 1. C-EDM experiment results.

	Experiment	1	2	3	4	5	6	7	8	9
Controlled parameters	Peak current (A)	38	38	38	47	47	47	55	55	55
	Voltage (V)	80	220	320	80	220	320	80	220	320
	On-time (μs)	16	32	64	32	64	16	64	16	32
	Off-time (μs)	128	256	512	512	128	256	256	512	128
	Average Ra (μm)	6.506	8.301	12.138	7.133	13.194	6.324	13.149	5.926	8.754



Level	A Peak current (A)	B Voltage (V)	C On-time (μs)	D Off-time (μs)
1	8.982	8.929	6.252	9.485
2	8.884	9.140	8.063	9.258
3	9.276	9.072	12.827	8.399
Delta	0.393	0.211	6.575	1.086
Rank	3	4	1	2

Fig 1. C-EDM main effect plot of means with data response of means.

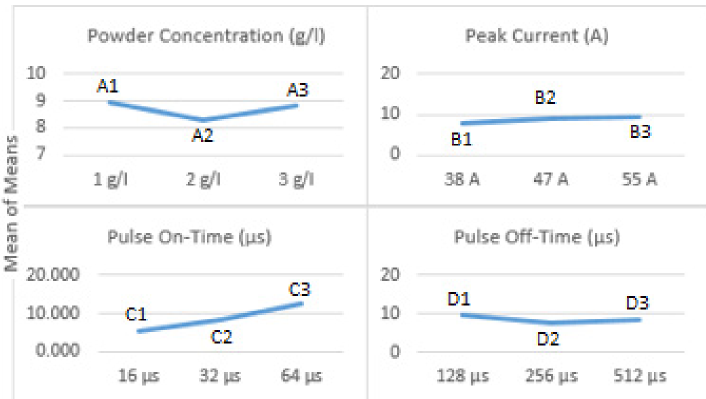
Table 1 indicates the average surface roughness obtained from the C-EDM experiments together with the controlled parameters of each experiment. Experiment eight with a parameter combination of 55 A peak current, 220 V voltage, 16 µs pulse on-time, and 512 µs pulse off-time obtained the lowest surface roughness value with 5.926 µm. On the other hand, experiment five, with a parameter combination of 47 A peak current, 220 V voltage, 64 µs pulse on-time, and 128 µs pulse off-time obtained the highest surface roughness value with 13.149 µm.

The main effect plot of means with the data response of means is shown in Fig. 1. The most significant parameter was the pulse on-time followed by the pulse off-time. Amongst the four parameters, voltage was less significant compared to the others. From the graphs, the parameter values at A2, B1, C1, and D3 were predicted to obtain the lowest surface roughness. The total mean for the C-EDM experiments was 9.047 µm. The optimum surface roughness value was projected using equation (1) and the result obtained was 5.322 µm.

$$M_{opt} = \overline{T} + \left(\overline{A2} - \overline{T}\right) + \left(\overline{B1} - \overline{T}\right) + \left(\overline{C1} - \overline{T}\right) + \left(\overline{D3} - \overline{T}\right) \tag{1}$$

Table 2. PM-EDM experiment results.

	Experiment	1	2	3	4	5	6	7	8	9
Controlled parameters	Particles concentration (g/l)	1	1	1	2	2	2	3	3	3
	Peak current (A)	38	47	55	38	47	55	38	47	55
	Pulse on-time (µs)	16	32	64	32	64	16	64	16	32
	Pulse off-time (µs)	128	256	512	512	128	256	256	512	128
	Average Ra (µm)	5.778	7.771	13.320	6.576	13.428	4.873	10.542	5.489	10.382



Level	A Powder concentration (g/l)	B Peak current (A)	C On-time (µs)	D Off-time (µs)
1	8.956	7.632	5.380	9.863
2	8.292	8.896	8.243	7.729
3	8.804	9.525	12.430	8.462
Delta	0.664	1.893	7.050	2.134
Rank	4	3	1	2

Fig 2. PM-EDM main effect plot of means with data response of means.

C-EDM and PM-EDM experiments have been conducted by applying the same set of parameters as the optimized C-EDM. The surface roughness values obtained were 5.561 µm from C-EDM and a smoother surface with 4.971 µm from PM-EDM with 1 g/l particle concentration. The surface quality was improved by 10.6% with PM-EDM. From this fact, it seems to promise to improve the EDM surface result by using the PM-EDM method.

There were also nine experiments with three times of repetitions carried out using the PM-EDM method with different parameter combinations and average surface roughness results as shown in Table 2. In the PM-EDM experiments, 80 V voltage was applied consistently throughout all nine experiments since it was identified as a lower significant parameter as mentioned in the C-EDM result. The lowest surface roughness value was obtained from experiment six with 4.873 µm. The combination of the parameters for experiment six was the 2 g/l particle concentration, 55 A peak current, 16 µs pulse on-time, and 256 µs pulse off-time. On the other hand, the highest surface roughness was obtained from experiment five with 13.428 µm. The combination of the parameters for experiment five was the 2 g/l particle concentration, 47 A peak current, 64 µs pulse on-time, and 128 µs pulse off-time. Ironically, both the lowest and highest surface roughness values were obtained from experiments with the 2 g/l conductive particle concentration. The early inference which can be made was that the concentration of the conductive particles had less of a significant effect on the result compared to the other parameters.

$$M_{opt} = \overline{T} + \left(\overline{A2} - \overline{T}\right) + \left(\overline{B1} - \overline{T}\right) + \left(\overline{C1} - \overline{T}\right) + \left(\overline{D2} - \overline{T}\right) \tag{2}$$

The results were then further analyzed using the Taguchi method. Fig. 2 shows the PM-EDM main effect plot of means with the data response of means. It indicates that the most significant parameter affecting the surface roughness was the pulse on-time followed by the pulse off-time. From the graphs, the parameter values at A2, B1, C1, and D2 were predicted to obtain the lowest surface roughness. The total mean for the PM-EDM experiments was 8.684 µm. The optimum surface roughness value was projected using equation (2) and the result obtained was 2.980 µm. It shows that the optimized surface roughness from the PM-EDM experiment was 2.342 µm, which was less than that for the C-EDM experiment.

5. Conclusion

It can be concluded that the optimized machining parameters established for the lowest surface roughness were the 2 g/l particle concentration, 38 A peak current, 16 µs pulse on-time, and 256 µs pulse off-time. The pulse on-time and pulse off-time were the most significant parameters in both the C-EDM and PM-EDM experiments. Even though the other three parameters in the PM-EDM experiments were found to be more significant in affecting the surface roughness, the addition of the zinc particles in the PM-EDM experiments did end up causing a positive effect on the machined surface quality. The conducted experiments proved that PM-EDM had reduced the machined surface roughness by 44% compared to C-EDM. This method is proposed in bio-medical implant manufacturing where the quality of the machined surface is extremely important.

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