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ORIGINAL ARTICLE

The effect of process parameters on machining of magnesium nano alumina composites through EDM

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Abstract The effects of electrical discharge machining (EDM) parameters on drilled-hole quality such as taper and surface finish are evaluated. Microwave-sintered magnesium nano composites (reinforced with 0.8 and 1.2 wt.% of nano alumina) are used as work materials. Experiments were conducted using Taguchi methodology to ascertain the effects of EDM process parameter. The process parameters such as pulse-on time, pulse-off time, voltage gap, and servo speed were optimized to get better surface finish and reduced taper. ANOVA analyses were carried out to identify the significant factors that affect the hole accuracy and the surface roughness. Confirmation tests were performed on the predicted optimum process parameters. Pulse-on time and the servo speed are identified as major response variables. Micro structural changes and the effects of nano particle reinforcement in the drilled hole were studied through SEM micrographs.

Keywords EDM · Magnesium composite · Nano alumina · Taguchi

1 Introduction

There is an increasing demand for light-weight materials. Owing to their lower density and better mechanical properties [1], nowadays, magnesium-based composites are becoming potential candidate materials for automotive and aerospace applications [2–4]. Technology of magnesium-based composites is in the developing stage. Although magnesium is a relatively softer material, magnesium-based metal matrix composites are difficult to be machined. Fabrication of miniaturized holes with high aspect ratio is a difficult task for magnesium-based composites by conventional drilling. Rapid tool wear, the breakage of tool and chip disposal from the miniaturized holes are the problems associated with machining of such composites. Due to the difficulties and stringencies involved in processing of magnesium-based composites, final shape of magnesium composites can be achieved through suitable machining technology.

Electric discharge machining (EDM) is one of the nontraditional machining techniques which is widely used to machine harder materials [5, 6]. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage for manufacturing of mold, die, automotive, aerospace and surgical components. Drilling is considered to be a vital machining operation for composites to realize the structural applications. For considerable weight reduction in high-technology applications, miniaturized holes are necessary. Conventional drilling of similar composites is difficult for such applications where the quality of hole is more crucial. The response variables (outputs) of interest are the important quality characteristics of holes. This includes the accuracy of diameter at the entrance and exit side of the hole and the surface finish inside the hole (roughness).

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Fig. 1 Micro EDM

EDM machining, wire-cut EDM of aluminum composites were studied by many researchers. In EDM machining of aluminum composite reinforced with micron-sized particles of SiC, the discharge is more irregular and larger current is necessitated. EDM drilling with rotary tubular electrode normally results in increased material removal rate (MRR), lower electrode wear rate (EWR) and improved surface finish [7–9].

Fig. 2 Mg nano alumina composite (12 mm length and Ø 6.5 mm)

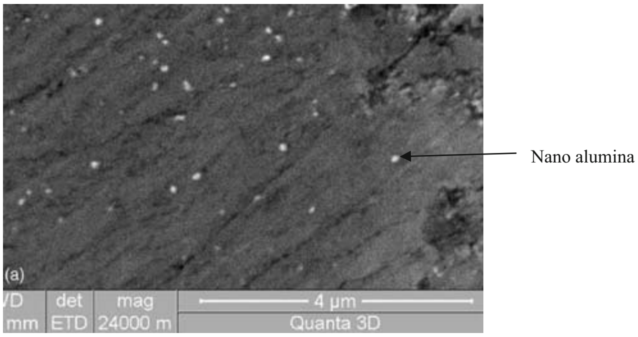

Fig. 3 Typical micrograph of magnesium nano alumina composite

Open gap voltage and pulse-on time are identified as significant influencing parameters on material removal rate in wire-cut EDM of aluminum composites [10]. Increase in the volume fraction of alumina reinforcement poses problems during machining. The interruption to machining is caused by the embedded alumina particles [11]. MRR, EWR, and surface roughness (SR) are considered for evaluating machinability of aluminum silicon carbide composites. Pulse duration has an inverse effect on all response variables such as MRR, EWR, and SR [12]. No report is presently available on EDM machining of magnesium-based metal matrix composites.

Magnesium nano alumina composite was fabricated through microwave-assisted powder metallurgy route. The manufacturing process of magnesium alumina composite was discussed by one of the authors elsewhere in detail [13]. The present work involves the study on the effect of process parameters on surface roughness and taper of the EDM-drilled holes on magnesium nano composites.

2 Taguchi experiment: design and analysis

2.1 Taguchi methods

Essentially, traditional experimental design procedures are too complicated to be used. It becomes laborious and cumbersome with the increase in number of process parameters. The Taguchi method solves this problem by a

Table 1 Properties of magnesium and its composites

Material	Macrohardness (HR15T)	UTS (MPa)	Ductility(%)
Mg	37	173	7.36
Mg + 0.8 wt% Al_2O_3	55	229	12.37
Mg + 1.2 wt% Al_2O_3	65	246	14.47

Table 2 Factors and their levels

Factor		Level I	Level II	Level III
T on	µs	2	3	4
T off	µs	3.5	4.5	5.5
Voltage gap (Sv)	V	2	3	4
Servo speed (SEN)	mm/min	24	50	82

special design of orthogonal arrays. The entire process parameters can be studied with a minimum number of experiments [14, 15]. The Taguchi method (orthogonal array) is widely utilized in engineering analysis and consists of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behavior of a given process. The advantages of this method are reduction of effort in conducting experiments, considerable savings in experimental time with decreased cost, and discovering significant factors in a faster way. In addition to the *S*/*N* ratio, a statistical analysis of variance (ANOVA) can be employed to indicate the impact of process parameters. From this, the optimal levels of process parameters can be estimated. Confirmation tests with the optimal levels of machining parameters were carried out.

2.2 Experimental work

Experiments were conducted using an ELECTRONICA small-hole super drill ED 32U machine shown in Fig. 1. Rotary brass hollow tubular electrode of diameter 0.5 mm is fed downwards into the work piece under servo control. De-ionized water was circulated as the dielectric fluid and it was injected at a pressure of 80 kg/cm^2 through the tubular electrode.

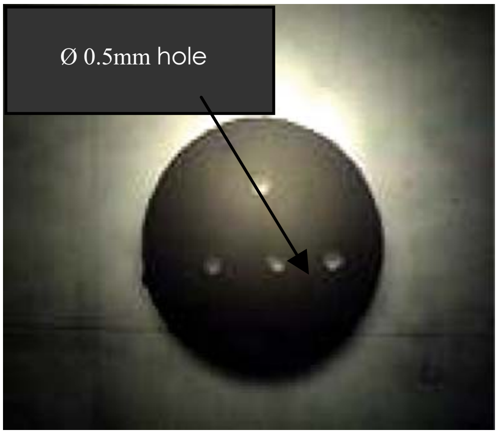

Fig. 4 Macrograph of EDM-drilled hole

Figure 2 shows the macrographs of the typical magnesium nano alumina composites (0.8 and 1.2 wt.%) used in this study. Figure 3 shows the micrograph of a typical composite explaining the uniform distribution of nano alumina particle in magnesium matrix. Microwave-sintered magnesium nano alumina composites were used as a work material here. The reinforced alumina particles had an average size of 30–50 nm. Magnesium with 0.8 and 1.2 wt.% nano alumina reinforcements are studied. The properties of these composites are presented in Table 1. For comparison, the properties of pure magnesium also have been presented in the same table. The factors and levels of machining parameters chosen for this study are presented in Table 2.

Table 3 L9 Orthogonal array

Exp.No	T on	T off	Voltage gap (Sv)	Servo speed (SEN)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

2.3 Plan of Taguchi's orthogonal arrays

Orthogonal arrays are highly utilized in engineering analysis. They consist of experiments which aim to acquire data about the behavior of a given process in a controlled

Table 4 Response variable values

Exp. no	0.8% Nano alumina		1.2% Nano alumina	
	Taper (degree)	Surface roughness (µm)	Taper (degree)	Surface roughness (µm)
1	0.0620	3.11	0.0365	3.658
2	0.0692	4.558	0.07083	5.2110
3	0.0909	4.080	0.08667	5.7650
4	0.0716	5.645	0.09703	6.0250
5	0.0819	4.133	0.03016	3.5630
6	0.0891	4.059	0.06043	5.6800
7	0.0970	8.098	0.1209	6.5110
8	0.1359	8.682	0.1536	7.0482
9	0.1232	3.725	0.0640	4.5670

Table 5 *S/N* ratio for taper (Mg + 0.8% nano alumina)

Factor	Level 1	Level II	Level III
T on	22.7263	21.8782	18.5933
T off	22.4377	20.7545	20.0055
Sv	20.8314	21.4258	20.9405
SEN	21.3546	21.4890	20.3541

Table 7 *S/N* ratio for taper (Mg + 1.2% nano alumina)

Factor	Level 1	Level II	Level III
T on	24.3263	25.0161	19.4995
T off	22.4511	23.2260	23.1648
Sv	23.1284	22.3781	23.3353
SEN	27.6759	21.9075	19.2584

way. The effects of several process parameters can be determined effectively by carrying out matrix experiments based on Taguchi's orthogonal design. The selected *L*9 orthogonal array for four factors and three levels is presented in Table 3.

2.4 Evaluation of response variables

Typical macrograph of EDM-drilled hole is presented in Fig. 4. The response variables Taper and surface roughness are calculated and tabulated in Table 4. Taper can be calculated from the expressions

$$\theta = \tan^{-1}((\mathrm{Djt} - \mathrm{Djb})/2H) \quad (1)$$

Where, Djt, and Djb are the diameters of the machined hole at the top and bottom of the workpiece and *H* is the height of the work piece. The work piece height is 12 mm. The hole size at the top and bottom were measured using profile projector. Surface roughness is measured using Taylor Hobson Precision-Form Talysurf 50 Model Talysurf Intra 112/3346-01 surface roughness measuring device. A diamond probe of 2 μm was used with the cut off length of 2 mm.

3 Preparation of mathematical models

3.1 Regression analysis

The mathematical model commonly used is represented by.

$$Y = f(Ton, Toff, voltage\ gap(Sv),\ S.Speed(SEN)) \quad (2)$$

Y denotes the response variables. Surface roughness and taper are the response variables. *f* is the response function and T on, T off, voltage gap S.Speed are the process variables. T on is the pulse duration during which the current is on and T off represents the duration with which current is in off position. Servo speed with which rotary electrode fed into the work piece is represented by servo speed [S.Speed (SEN)].

A simple regression analysis was performed to demonstrate the fitness of the experimental measurements. MINITAB statistical software is used. First-order nonlinear polynomial model was developed. Generally, the fitness characteristic is shown by the following equation

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \varepsilon \quad (3)$$

Where β_1, $\beta_2 \ldots$ β_4, are the estimates of the process parameters, and ε is error. An empirical equation is then derived to describe the functional relationship between the response variables to the process parameters.

The regression equation for 0.8% alumina

$$\begin{aligned}\text{Taper} = {} & -0.0316 + 0.0224\ \text{T on} + 0.0121\ \text{T off} \\ & - 0.00285\ \text{Sv} + 0.000190\ \text{SEN} \ldots R^2 84.3\end{aligned} \quad (4)$$

$$\begin{aligned}\text{S.Roughness} = {} & 2.08 + 1.46\ \text{T on} - 0.830\ \text{T off} \\ & + 0.075\ \text{Sv} + 0.0418\ \text{SEN} \ldots\ldots R^2 82.4\end{aligned} \quad (5)$$

Table 6 *S/N* ratio for surface roughness (Mg + 0.8% nano alumina)

Factor	Level 1	Level II	Level III
T on	−11.7480	−13.1828	−16.1208
T off	−14.3520	−14.7577	−11.9418
Sv	−13.6058	−13.2104	−14.2354
SEN	−11.2010	−14.5109	−15.3396

Table 8 *S/N* ratio for surface roughness (Mg + 1.2% nano alumina)

Factor	Level 1	Level II	Level III
T on	−13.6064	−13.9075	−15.4757
T off	−14.3790	−14.1121	−14.4985
Sv	−14.4378	−14.3767	−14.1751
SEN	−11.8313	−15.2328	−15.9256

Table 9 ANOVA for taper, using adjusted SS for test (Mg + 0.8% Nano Alumina)

Source	*df*	Seq.SS	Adj.SS	Adj.MS	*F*	*P*	% Contribution
T on	2	0.0034786	0.0034786	0.0017393	36.96	0.026	71.40
T off	2	0.0009682	0.0009682	0.0004841	10.29	0.089	19.87
Sv#	2	0.0000941	0.0000941	0.0000471			
SEN	2	0.0003309	0.0003309	0.0001655	3.52	0.221	6.79
Error	2	0.0000941	0.0000941	0.0000471			1.94
Total	8	0.0048718					100

Table 11 ANOVA for taper, using adjusted SS for tests (Mg + 1.2% nano alumina)

Source	*df*	Seq.SS	Adj.SS	Adj.MS	*F*	*P*	% Contribution
T on	2	0.0048543	0.0048543	0.0024271	79.04	0.012	38.84
T off	2	0.0004197	0.0004197	0.0002098	6.83	0.128	3036
Sv#	2	0.0000614	0.0000614	0.0000307			
SEN	2	0.0071875	0.0071875	0.0035937	117.03	0.008	57.50
Error	2	0.0000614	0.0000614	0.0000307			0.49
Total	8	0.0125228					

The regression equation for 1.2% alumina

$$\begin{aligned}\text{Taper} = &- 0.0144 + 0.0241\ \text{T on} - 0.00723\ \text{T off} \\ &- 0.00215\ \text{Sv} + 0.00118\ \text{SEN}\ldots R^2 86.4\end{aligned} \tag{6}$$

$$\begin{aligned}\text{S.Roughness} = &\ 1.94 + 0.582\ \text{T on} - 0.030\ \text{T off} \\ &- 0.091\ \text{Sv} + 0.0395\ \text{SEN}\ldots\ldots\ldots R^2 85.9\end{aligned} \tag{7}$$

The values of $R^{2,}$ for surface roughness and taper were computed. The simple regression models for surface roughness and taper suited very well with the experimental data.

4 Result and discussion

4.1 Mechanism of material removal

Conventional drilling is difficult to be performed on MMC's due to increased tool wear and associated problems. These problems become more severe for smaller-sized holes. The electrical and thermal insulating properties of the reinforcement particles generally pose problems. Melting and vaporizing of matrix material is the proposed mechanism for EDM machining of composites. Melting and vaporization of matrix material by the plasma channel detaches the reinforced particles. The presence of unmelted ceramic particles with its cutting edges in the debris collected, confirmed the proposed mechanism for composites. This mechanism agreed well with the earlier findings [16, 17].

Owing to the insulating nature of reinforcement particles, abnormal arcing and random spark discharges occur for micron-sized reinforcements. Fall out of particles can be observed due to the impact of spark. Bands and craters observed at the machined surfaces of composites confirm the irregular spark discharges during machining. Nano-sized reinforcement avoids such problems. In the case of nano-sized particle reinforcement, no such abnormal arcing phenomenon is observed. Damages observed at the machined surfaces are comparatively at a lower order. The obtained variation in surface roughness (Ra = 3–8 μm) for all the selected experimental conditions is also minimal. This improvement in the hole quality can be attributed to the process efficiency and the nano-sized reinforcement.

Since the electrode is advancing towards the work, the removal of reinforcement particles from the matrix is difficult, for conventional EDM process. But in the case of rotary EDM, removal of debris is easier. When the spark is generated, magnesium is melted and the reinforcement particle is also flushed away. The quality of the hole produced by this rotary EDM is superior owing to the improvement in

Table 10 ANOVA for surface roughness, using adjusted SS for test (Mg + 0.8% nano alumina)

Source	*df*	Seq.SS	Adj.SS	Adj.MS	*F*	*P*	% Contribution
T on	2	13.9355	13.9355	6.9678	13.04	0.071	44.53
T off	2	6.1444	6.1444	3.0722	5.75	0.148	19.63
Sv#	2	1.0686	1.0686	0.5343			
SEN	2	10.1457	10.1457	5.0728	9.49	0.095	32.42
Error	2	1.0686	1.0686	0.5343			3.41
Total	8	31.2942					

Table 12 ANOVA for S.Roughness, using adjusted SS for tests (Mg + 1.2% nano alumina)

Source	DF	Seq.SS	Adj.SS	Adj.MS	F	P	% contribution
T on	2	2.3074	2.3074	1.1537	100.14	0.010	19.79
T off	2	0.0230	0.0230	0.0115			
Sv[a]	2	0.0712	0.0712	0.0356	3.09	0.244	0.61
SEN	2	9.2539	9.2539	4.6269	401.60	0.002	79.39
Error	2	0.0230	0.0230	0.0115			0.19
Total	8	11.6555					

[a] not significant

flushing, and reduction in tool wear. The possibility of abnormal arcing due to the insulating particles is reduced here, due to the size effect.

4.2 Analysis of *S*/*N* ratio

S/*N* ratio is the ratio between the desired and undesired value. Normally, signal (*S*) is the desired value and noise (*N*) is the undesired value. The *S*/*N* ratio characteristics can be divided into three categories: nominal the better, smaller the better, and larger the better. Taguchi uses the *S*/*N* ratio to measure the quality characteristic which deviates from a desired value. The *S*/*N* ratio η is:

$$\eta = -10 \times \log_{10}\left[(1/N) \times \sum \left(y^2{}_i\right)\right] \text{ for } i = 1 \text{ to N} \quad (8)$$

For improved dimensional accuracy and better hole quality, minimizing the taper and surface roughness is essential. Hence, smaller-the-better quality characteristic was selected. Where Y_i is the value of surface roughness for the *i*th test; *n* is the number of tests; and *N* is the total number of data points. Thus, the *S*/*N* ratio values were calculated using Eq. 8. The surface roughness Ra and taper values were measured from the experiments and the *S*/*N* ratio values are presented in Tables 5, 6, 7, and 8. From this, the optimum process parameter was selected.

4.3 Analysis of variance (ANOVA)

ANOVA was carried out to examine the influence of process parameters on quality characteristics. ANOVA results are illustrated in Tables 8, 9, 10, and 11. The *F*-ratio corresponding to the 95% confidence level of the accurate calculation of process parameters is *F* 0.05

By observing Tables 9, 10, 11, and 12, it can be understood that the taper was influenced by pulse-on time. Servo speed plays a vital role in surface roughness. Figure 5 shows the variation of taper and surface roughness for 0.8 and 1.2% Nano alumina, respectively.

Figure 4 presents the variation of taper with different levels of parameters. It can be understood that in order to get minimized taper, pulse-off time should be at a higher level, where as T on and servo speed and voltage gap should be at the minimum level. By increasing the time between two consecutive sparks, lower amount of heat flux can be generated. The faster removal of heat by the dielectric fluid results in reduced taper. Variation of surface roughness with different level of parameters T on, T off, voltage gap, and servo speed are presented in Fig. 5. Servo speed has more influence on surface roughness. Lower level of servo speed, lower level of T on, voltage gap, and T off should be selected to minimize the surface roughness. A validation experiment was conducted for the obtained best levels of parameters. Table 13 shows the comparison of predicted and experimental results. In the case of taper,

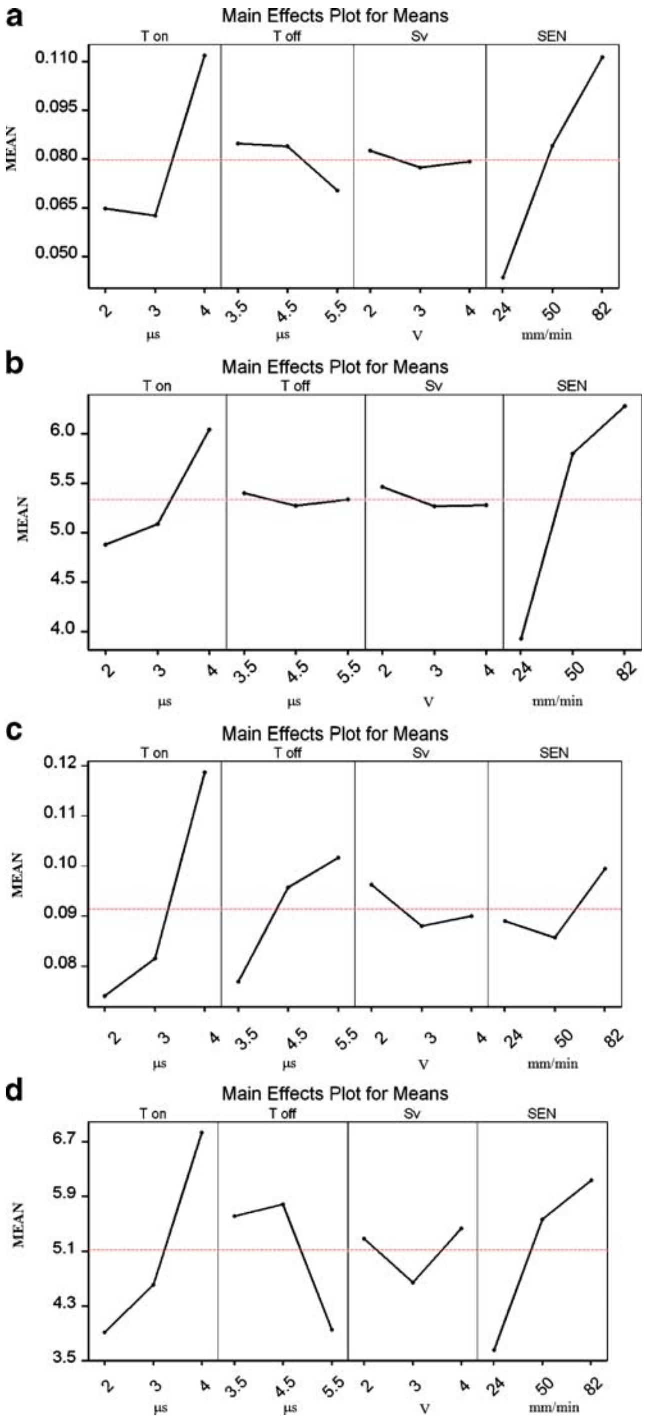

Fig. 5 **a** Variation for 1.2% alumina for taper; **b** variation for 1.2% alumina for surface roughness; **c** variation for0.8% alumina for taper; **d** variation for0.8%alumina for surface roughness

Table 13 Comparison of experimental and predicted result

		Optimum machining parameter			
		0.8 % Nano alumina		1.2 % Nano alumina	
		Predicted	Experimental	Predicted	Experimental
Taper	Level	A1B1C2D2	A1B1C2D2	A2B2C3D1	A2B2C3D1
	Taper	0.0565	0.0612	0.04509	0.0461
	S/*N* ratio for taper	24.9590	24.2649	26.9184	26.7259
Surafce Roughness	Level	A1B3C2D1	A1B3C2D1	A1B2C3D1	A1B2C3D1
	Ra	1.6632	3.4090	3.553	4.6977
	S/*N* ratio for Ra	−4.4188	−10.6525	−11.0119	−13.4377

predicted and experimental values are almost equal for both 0.8 and 1.2 wt.% of nano-alumina-reinforced composites. But, in the case of surface roughness, the predicted and experimental values have acceptable variation.

5 SEM analysis

The groove section is analyzed through scanning electron microscopy. Figure 6 shows the macrograph of the sectioned EDM-drilled hole.

SEM micrographs presented at Figs. 7 and 8 are observed at the location A & B of Fig. 6, respectively. The location A is selected to assess the damages at the side wall of the hole. The damages observed at this zone can be understood by Fig. 7. The recast layer observed at location B is attributed to the series of succeeding sparks and the generation of a high amount of heat. Hence, the reduction of damages during machining is a difficult task. The parameters are optimized to reduce the size of the recast layer to 18 μm.

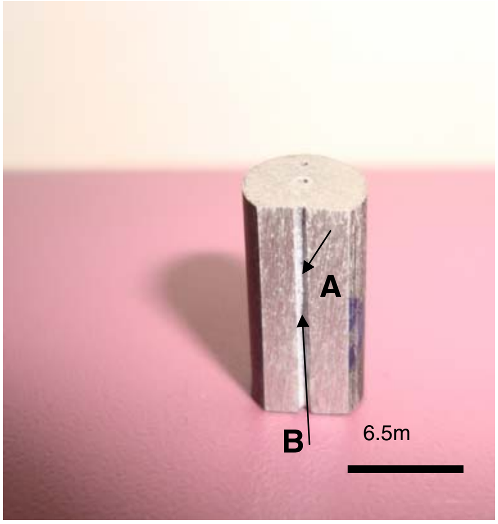

Fig. 6 Sample specimen for the EDM-drilled hole

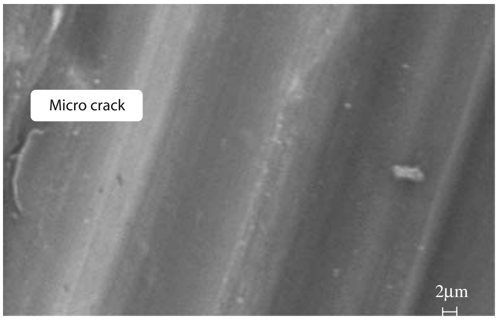

Fig. 7 SEM micrograph of micro crack

6 Conclusion

- High aspect ratio holes (0.5 mmΦ and 12 mm height) were drilled in magnesium nano composites by electric discharge machining.
- The surface roughness and taper were studied with respect to pulse-on time, pulse-off time, voltage gap, and servo speed. A regression model was developed. The results were validated through ANOVA. A confirmation test was carried out.
- From the analysis, it is observed that surface roughness and taper mainly depends on servo speed and pulse-on time.
- By optimizing the process parameters, the damages on the mechanical surfaces such as recast layer and hairline cracks are minimized.

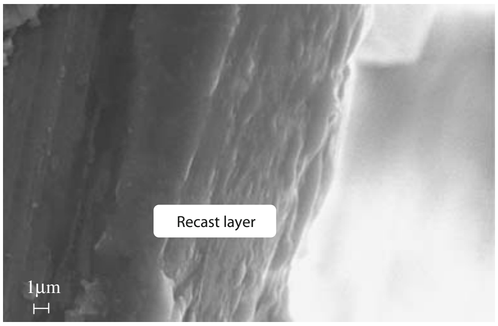

Fig. 8 SEM micrograph of recast layer

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