Primary study on machiability of aluminium matrix composite using WEDM

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***Abstract*—The main goals of wire electrical discharge machining (WEDM) manufacturers and users are to achieve a better stability and high productivity of the manufacturing process. The investigation on machinability of Aluminium Matrix Composite (AMC) using Wire-cut Electric Discharge Machining (WEDM) machine is constructed. The aim of this project to determine the most optimum machining parameter that will be increased the machinability of AMC based on material removal rate (MRR). A series of experiments have been performed on AMC reinforced 5 % alumina (Al_2O_3) with dimension 100mm x 3 mm x 4 mm. The test specimens have been cut by using different machining parameter combinations on the Sodick AQ327L WEDM machine in the Teaching Factory of Universiti Malaysia Perlis (UniMAP).The Full Factorial Design of Experiment approach with two levels was used to determine the combination of machining parameter based on Pulse-off time (µs), Servo Voltage (V), and Wire Tension (gf/mm). The result of calculated MRR was analyzed using Regression Analysis Method to determine the mathematical model between machining parameter and machining characteristics.**

***Index Terms*—WEDM; Aluminium Matrix Composite; Design of Experiment;**

I. Introduction

Increasing quantities of metal matrix composites (MMCs) are being used to replace conventional materials in many applications, especially in manufacturing and automotive industries. However, MMCs were used only for special purposes because of the difficulties encountered in their machining [1-4], even though the potential of MMCs for significant improvements in performance over conventional alloys has been recognized [7].

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Amongst various machining methods, Wire-cut Electrical Discharge Machining (WEDM) is one of the most versatile and useful technological processes for machining intricate and complex shape in various conductive materials [3-9], but the surface integrity after machining is a problem. For this project, aluminium matrix composites (AMC) that one of MMC group were used as an experiment subject. By using WEDM process, investigations on machinability of aluminum matrix composite were prepared. The machinability of aluminium matrix composite that were investigated is based on parameter machining of WEDM machine such as pulse-off time, wire tension, servo voltage and others parameter. The machining parameters can be set for optimum machining with knowledge of the effect of the machining parameters on the surface roughness (SR) and material removal rate (MRR) of the process, as a result of the investigation study. [2]

The experiment must be constructed to investigate effect on material removal rate (MRR) when cutting Aluminium Matrix Composite (AMC). The machining parameters that will give effect on MRR of AMC must be selected. The result data of MRR must be analyzed to get the cause-effect and relationship between machining parameters and machining performance. Then from the analysis result, the optimum machinability of machining AMC using WEDM will be obtained.

Objective is a mission, purpose, or standard that can be reasonably achieved within the expected timeframe and with the available resources. In this project, the main objective is a investigating and developing the optimum machinability of AMC using WEDM. The machinability that investigating is material removal rate (MRR) of AMC. The machining parameters that will give effect to MRR selected is pulse-off time, servo voltage and wire tension. Then, the relationship of the effects of machining parameter on material removal rate (MRR) is analyzing using regression analysis. In additional objective are:

- To analyze the most machining parameter that give greater influence on MRR of AMC during machining by WEDM using regression method analysis.
- To analyze effect of wire breakage during cutting AMC by WEDM.
- To investigate the optimum machining parameter that can increase machining rate.

Machinability data for WEDM machining process is usually referred to the selection of pulse duration, current discharge, servo voltage, voltage, wire tension, wire speed, fluid pressure and others parameter based on selected WEDM machine used. Machinability data selection plays an important role in the efficient utilization of machine tools and thus significantly influences the overall manufacturing costs. It has become more and more important especially in computer-integrated manufacturing and computer aided manufacturing. The main objective of machining is to satisfy the demand of the work-piece dimensions and its surface finish. The machinist is subjected to a wide range of possible pulse duration, current discharge, servo voltage, voltage, wire tension, wire speed, fluid pressure and other machining parameters. The application of machining economics to shop floor practice has been limited and the correct choice of machining conditions is normally overlooked, the reasons for which are [8].

II. METHODOLOGY

The samples were machined on an AQ327L WEDM machine of Sodick Europe Ltd. with an isopulse generator and pure water was used as the dielectric liquid. With Sodick's new LP Control it can import Parasolid (solid models) files directly into the control. This unique feature maximizes the cutting efficiency, reduces the workflow and reduces programming.

Figure 1. The Sodick AQ327L Machine

A. Material

The material used in this project is an Aluminium Matrix Composite. This material is produced by using powder metallurgy process.The material used in this experiment is an Aluminium Matrix Composite (AMC) reinforced with 5 % of Alumina (Al_2O_3). Type of alumina that reinforced with aluminium is fiber type. The alumina that reinforced in this sample has fiber type. The fibers can either be parallel or pre woven, braided prior to the production of composite.The dimension of sample that was cut is a 100 mm (length) x 10mm (width) x 4 mm (thickness). The sample is cut using open cutting setting that is means the cutting operation only cut the straight line on the sample without complex cutting design.

Figure 2. Sample of AMC reinforced with 5% Alumina after Cutting

B. Design of experiment

In order to get optimum and accurate result, Design of Experiment (DOE) technique is used to collect data. DOE is a structured, organized method that is used to determine the relationship between the different factors affecting a process and the output of that process.

In this experiment, the machinability of AMC reinforced short fiber was analyzed. The effect of machining parameters that are pulse-off time (OFF), servo voltage (SV) and wire tension (WT) on the surface roughness (SR) and material removal rate (MRR) of AMC reinforced with 5 % alumina were evaluated to investigate the maximum MRR. Furthermore, the effect of wire breakage when cutting the AMC reinforced short fiber on the machinability was studied.

The experiment performed in this study was a screening experiment. The experimental strategy used in this experiment was full factorial design (2^k) where k is the number of controlled variables in the experiment. In this experiment, there were three controlled variables investigated including pulse-off time (OFF), servo voltage (SV) and wire tension (WT).

These machining conditions were chosen based on typical operating conditions of the machine recommended for cutting tool steels. Each machining condition had one replications; therefore, the total number of experimental trials was 8. Replication of experiment has two important characteristics. First, it allows the experimenter to obtain an estimate of the experimental error. This estimate of error becomes a basic unit of measurement for determining whether observed differences in the data are really statistically different. Second, if the sample mean is used to estimate the effect of a factor in the experiment, then replication permits the experimenter to obtain a more precise estimate of this effect.

The number of Level is 2 levels of each factor were selected for the 2^k experiment as follows: pulse-off times (OFF) at 119 and 150 ms; servo voltage (SV) at 40 and 60 V; wire tensions (WT) at 1600 and 1750 gf/mm^2. This value was selected randomly and the total sample that was cut is 8. The other machining parameters are keep constant refer to Table I.

TABLE I.
OTHER CONSTANT MACHINING PARAMETER

No.	Parameter	Value	Unit
1	Pulse-on Time (ON)	006	Ms
2	Discharge Current (IP)	2215	A
3	Voltage (V)	8	V
4	Peak Current (PIK)	0	A
5	Wire Speed (WS)	100	
6	Water Pressure	040	Pa
7	WK	025	
8	HRP	0	
9	MAO	260	
10	SF	0350	mm/min
11	C	0	
12	CTRL	0	

C. *Workpiece Preparation*

The original sample dimension that was cut is 100 mm (length) x 10mm (width) x 4 mm (thickness). The sample is cut for 8 times with different machining parameter that was constructed using DOE. The 3 mm length was cut horizontally for 8 times.

D. *Conduct the experiment*

Before the first cutting is started, the weight of material is taken. Then after each cutting operation using WEDM machine is finished, the weight of sample material is taken using Digital Electronic Balancer. This data taken is used to calculate the value of material loss rate or also known as material removal rate (MRR) after each operation. The mathematical formula used to calculate MRR is:

Loss of weight (g)= Weight before experiment – weight after experiment

Volumetric material loss (cm^3) =
$$\frac{\text{Loss of weight (g)}}{\text{Density of materials (g/cm}^3\text{)}}$$

Materials Removal Rate (MRR) (mm^3/mm) =
$$\frac{\text{Volumetric materials loss (mm}^3\text{)}}{\text{Machining time (min)}}$$

Then all the result of data of MRR is analyzed using regression method analysis to compile the optimum machining parameter that influenced most on MRR of sample. The mathematical model that constructed by regression method is interpreted to evaluate the correlation between machining parameter and machining performance. All the result analysis will be perform in scatter graph. According to quality engineering [6], the characteristic that the higher observed value represents the better machining performance in the case MRR is known as ‘higher the better” (HB). The S/N ratio (signal-to-noise ratio) could be an effective representation to find the significant parameter from those controlling machining parameters by evaluating the minimum variance.

For confirmation result of experiment, the optimum machining parameter will be set on WEDM machine. The actual machining response for this machining parameter will be compare to the obtained result of MRR and SR for machining parameter determined by DOE. If the error between the results does not exceed 10%, the experiment is valid. If not, the experiment will be repeat over again until the comparation result is valid.

III. RESULT AND ANALYSIS

The AMC with 5% fiber material with dimension 100 mm × 10 mm × 4 mm was machined using open machining by WEDM machine. The materials were cut with width 3 mm for every sample and weight before and after machining were weighted by Digital Electronic Balancer. There are 8 sample were cut and three WEDM machine parameter was changed with two different value for every sample. During the machining, time was taken using stopwatch. There are the experimental result from the machining was presented in TABLE II

A. *Analysis of Result*

The chosen three parameters have different influences on the machining performance. By regression analysis, mathematical models relating the machining performance to various machining parameters are established and the optimal machining-parameters setting is obtained using non-linear regression analysis method. By using the experiments and applying regression analysis, the modeling the desired response to several independent input variables can be obtained [2].

By properly randomizing the experiment, the effects of extraneous factors of confounding variables that may be present are averaged out. Confidence level of 95% ($\alpha = 0.05$) was used throughout analyses of the experiment. In addition, high order-order interactions were neglected in this screening experiment. Only main effects were included in the analysis. The general mathematical model of regression method in this experiment can be expressed as Equation 4.20:

$$\frac{X_4}{s_4} = a_1\left(\frac{x_1}{s_1}\right) + a_2\left(\frac{x_2}{s_2}\right) + a_3\left(\frac{x_3}{s_3}\right)$$

where, a1, a2,and a3 are determined by solving simultaneously the equations:

$$a_1 r_{11} + a_2 r_{12} + a_3 r_{13} = r_{14}$$
$$a_1 r_{21} + a_2 r_{22} + a_3 r_{23} = r_{24}$$
$$a_1 r_{31} + a_2 r_{32} + a_3 r_{33} = r_{34}$$

and where;

x_j : and j=1,2,3, and 4

The regression analysis for actual MRR result was performed to study influences of the WEDM machining variables. Before looking at the results from regression analysis for this study, assumptions of normality, independence, and constant variance of residuals were examined. Here the regression equation of actual MRR versus pulse-off time (OFF), servo voltage (SV) and wire tension (WT) that evaluated from Minitab software:

MRR = 1.79 + 0.832 OFF - 0.258 SV - 0.578 WT

TABLE II.

RESULT OF MACHINING SAMPLE OF AMC USING WEDM MACHINE

No. of Sample	Factor Parameter Control			Result						
	Pulse Off Time (µs)	Servo Control	Wire Tension (gf/mm²)	Weight Before (g)	Weight After (g)	Total Weight (g)	Time (sec)	Sample Weight (g)	Volume Sample (mm³)	Density (g/mm³)
1	119	60	1750	8.165	7.784	0.381	100	0.338	122.5	2.761×10^3
2	150	40	1600	6.604	6.224	0.379	68	0.343	122.5	2.804×10^3
3	119	60	1600	8.565	8.165	0.399	91	0.344	122.5	2.808×10^3
4	150	60	1600	6.224	5.839	0.385	129	0.348	122.5	2.843×10^3
5	119	40	1750	7.784	7.400	0.383	54	0.336	122.5	2.745×10^3
6	150	60	1750	6.944	6.604	0.340	120	0.347	122.5	2.839×10^3
7	150	40	1750	7.400	6.944	0.456	79	0.345	122.5	2.822×10^3
8	119	40	1600	5.839	5.453	0.386	51	0.347	122.5	2.839×10^3

Normality of residuals was first checked using a normal probability plot. The normal probability plot of residuals for this experiment is shown in Fig. 3. Linearity of this normal plot was suspicious. Further analysis using coefficient of correlation of the plot was then performed. Using 95% confidence level, when the number of residuals is 8, the critical value of coefficient of correlation between residuals and its percent under normality is 0.632. From Fig 3. the correlation coefficient of the plot was 0.456, which is less than its critical value and has weal strength of a linear relationship. This indicates that the normal distribution of residuals was not satisfied.

TABLE III

LIST OF VALUE MACHINING PARAMETERS FOR REGRESSION ANALYSIS CALCULATION

N	X_1	X_2	X_3	X_4	X_1^2	X^2	X_3^2	X_4^2	X_1X_2	X_1X_3	X_1X_4	X_2X_3	X_2X_4	X_3X_4
1	119	60	1750	0.00381	14161	3600	3062500	1.454E-05	7140	208250	0.453	105000	0.228	6.674
2	150	40	1600	0.00558	22500	1600	2560000	3.114E-05	6000	240000	0.837	64000	0.223	8.929
3	119	60	1600	0.00439	14161	3600	2560000	1.928E-05	7140	190400	0.522	96000	0.263	7.025
4	150	60	1600	0.00298	22500	3600	2560000	8.911E-06	9000	240000	0.447	96000	0.179	4.776
5	119	40	1750	0.00710	14161	1600	3062500	0.0000504	4760	208250	0.844	70000	0.284	12.425
6	150	60	1750	0.00283	22500	3600	3062500	8.027E-06	9000	262500	0.425	105000	0.170	4.958
7	150	40	1750	0.00577	22500	1600	3062500	3.337E-05	6000	262500	0.866	70000	0.231	10.110
8	119	40	1600	0.00756	14161	1600	2560000	5.725E-05	4760	190400	0.900	64000	0.302	12.106
	$\sum X_1$=	$\sum X$=	$\sum X_3$ =	$\sum X_4$ =	$\sum X_1^2$ =	$\sum X^2$ =	$\sum X_3^2$ =	$\sum X_4^2$ =	$\sum X_1X_2$=	$\sum X_1X_3$ =	$\sum X_1X_4$ =	$\sum X_2X_3$=	$\sum X_2X_4$ =	$\sum X_3X_4$ =
	1076	400	13400	0.04004	146644	20800	22490000	0.000165	53800	1802300	5.298	670000	1.882	67.006

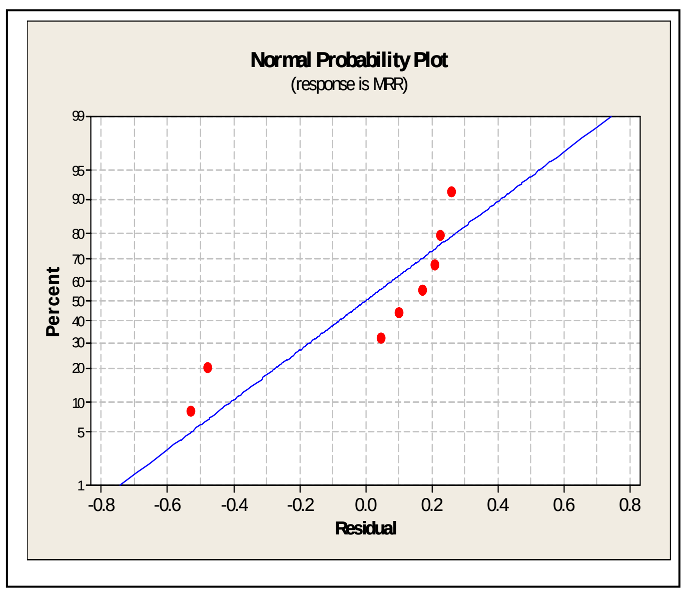

Figure 3. Normal Probability Plot

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Fig. 4 shows plotting of the residuals in time order of data collection. This method is helpful in checking independence assumption on the residuals. It is desired that the residual plot should contain no obvious patterns. However, it is noticeable from Fig. 3 that determination of the pattern is subjective to the experimenter's experience, and could be biased. Thus, Durbin-Watson test was employed to check independence assumption on the residuals. Durbin-Watson test statistic for this experiment was 1.20357.

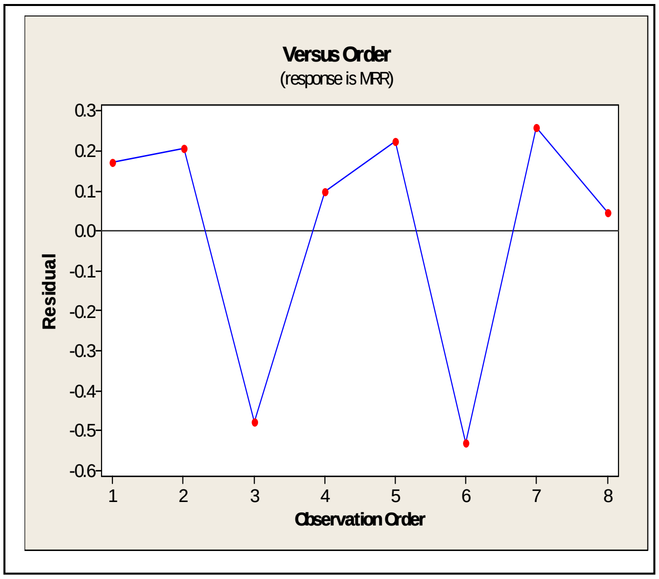

Figure 4. Residuals in Time Order Plot

Shown in Fig. 5 is plot of residuals versus predicted values. This plot is the typical testing for the assumption of constant variance. If the assumption is satisfied, the residual plot should be structure less. It is obvious that it is subjective and difficult to determine whether the plot is structured.

From the statistical analysis, effects of the three main variables on MRR of the WED Med AMC are shown in TABLE IV. Based on evidence, at 95% confidence level ($\alpha = 0.05$), servo voltage had significant effect on MRR of the sample surface (p-value < 0.05), where as pulse-off time and wire tension did not affect the MRR (p-value > 0.05).

From Fig. 6 plots of main effects, when value of servo voltage is decreased, the MRR of the machining is increased. This is because, the higher value of SV will decreases the number of electric sparks, stabilizing electric discharge, although the machining rate is slowed down. Hence, to obtain a high MRR of WED Med sample, servo voltage should be set as low as possible.

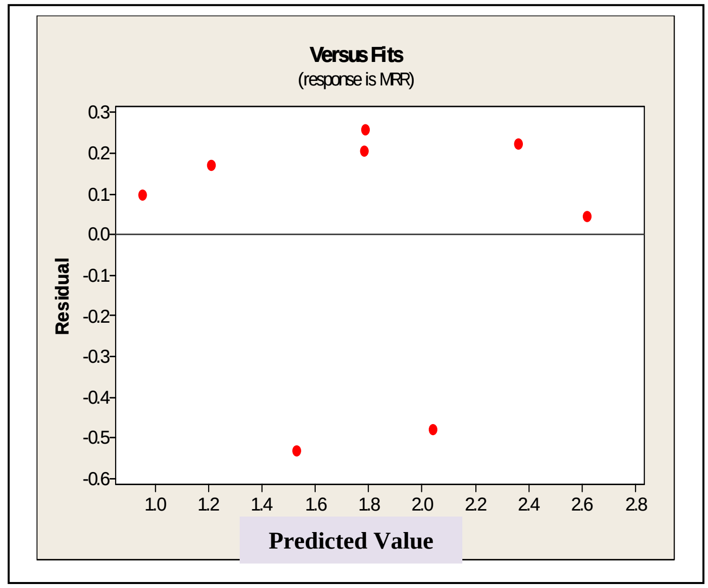

Figure 5. Residuals versus Predicted Value Plot

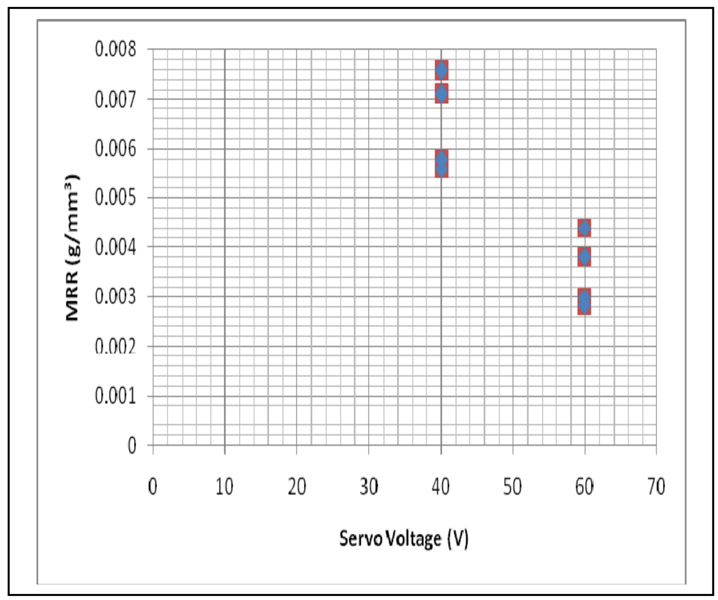

Figure 6. Plot MRR versus Servo Voltage (SV)

TABLE IV
VALUE OF P FOR MACHINING PARAMETER

Predictor	Coef	SE Coef	T	P	VIF
Constant	0.005257	0.002137	2.46	2.46	0.070
OFF	0.0007095	0.0008077	0.88	0.429	1.000
SV	-0.0024054	0.0008077	-2.98	0.041	1.000
WT	0.0015283	0.0008077	1.89	0.131	1.000

IV. DISCUSSION

During the machining of the sample using WEDM machine, a lot of wire were breakage and reduce the time efficiency of machining. This happened because AMC have greater hardness and it must be set using graphite setting before machine it. Besides, AMC have fiber composition and wire breakage could happen when the work piece contains impurity. Other than that, the setting also must be suitable to prevent wire breakage. The solutions to prevent wire breakage are:

1. Check the conductivity piece. When machining gap is too deep, the efficiency of discharge will be low, and wire breakage may occur. So the place of the conductivity piece must be adjusted.
2. Increase the value for the machining condition parameter “OFF” by 1 or 2. Increase it further when there is no apparent effect after increasing current.
3. Increase the value for the machining condition parameter “SV” by 1 to 5. The increase of SV can widen discharging gap, convenient for the removal of chip.

From the regression analysis of the machined sample, SV was predicted that influenced the rate of MRR. When the SV is decreased, the MRR is increased. When a smaller value is set for SV, the mean gap becomes narrower, which leads to an increase in number of electric sparks. It can be speed up the machining rate, however, the state of machining at the gap may become unstable, resulting in wire breakage. So it also can reduce machining time efficiency but SV can be lowest as it can if the other machining parameter that can influenced wire breakage is increased.

V. CONCLUSION

A methodology to determine the optimal machining parameters setting of AMC reinforced 5 % alumina by WEDM was proposed. This methodology is not only time saving and cost effective but also efficient and precise in determining the machining parameters. The machining variables included pulse-off time, servo voltage and wire tension. The variables affecting the surface roughness and metal removal rate were identified using regression analysis technique.

Results of this investigation lead to the following conclusions:

1. The servo voltages have significant influence on the material removal rate (MRR). Lower value of servo voltage can increased MRR and machining production rate will be increased simultaneously.
2. So that, to gives very good quality of AMC reinforced with 5% alumina by increase its material removal rate, the value of pulse off time and wire tension must be set as high as possible which is in this research the value of OFF and WT value set to 150 µs and 1750 gf/mm and servo voltage must be set as lowest as can which is 40 V.

Therefore, adjusting the pulse-off time setting is an appropriate strategy to control the discharging frequency for the prevention of wire breakage. The material of sample also must be properly cleaned by any type of oil to prevent wire breakage causes by discharge stopped.

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