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# Process Parameters Modelling Of Wire Electrical Discharge Machining On Al/Sic$_{10\%}$ MMC Using Dimensional Analysis

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**Abstract**— The complex phenomenon of wire electrical discharge machining (WEDM) is reducing its utilization to process aluminium silicon carbide with 10% weight metal matrix composite (Al/SiC$_{10\%}$ MMC) for industrial applications. This paper presents an experimental investigations and development of mathematical models using dimensional analysis for selection of WEDM process parameters. Sequential classical experimentation technique has been used to perform experiments for triangular, circular and rectangular shape cuts on Al/SiC$_{10\%}$ MMC as majority of industrial products are manufactured by these shapes or combinations. An attempt of mini-max principle and linear programming (LPP) has been made to optimize the range bound process parameters for maximizing material removal rate and minimum surface finish to machine Al/SiC$_{10\%}$ MMC. The test results proved that MRR and Ra values were significantly influenced by changing important five dimensionless π terms. The process parameters grouped in π terms were suggested the effective guidelines to the manufacturer for improving productivity by changing any one or all from the available process parameters.

**Index Terms**— Stir casting, Al/SiC$_{10\%}$ MMC, dimensional analysis, Buckingham's π theorem, regression analysis, Mini-max principle, linear programming.

## 1 INTRODUCTION

Presently aluminium based composites with SiC and $Al_2O_3$ particles are attracted for many engineering industrial applications because of their high temperature strength, fatigue strength, damping strength, wear resistance and low friction coefficient[1].However, machining of Al/SiC$_{10\%}$ MMCs using convention tool materials is very difficult due to presence of abrasive reinforcing phase which causes severe tool wear[2],[3],[4]. Recently wire electrical discharge machining (WEDM) widely used in industries for precise, complex and irregular shapes of difficult- to- machine electrically conductive materials. In this operation, the material removal occurs by the ignition of rapid and repetitive spark discharges between the gaps of workpiece and tool electrode connected in an electric circuit. A small wire of diameter 0.05 -0.3 mm is continuously supplied from spool to work piece with a maintained gap of 0.025-0.05 mm between wire and workpiece [5],[6],[7]. Because of complicated stochastic process mechanism of machining, the selection of process parameters for obtaining higher cutting efficiency and accuracy is still not fully solved, even with the most up-to-date CNC WEDM machine [8]. Scot et al. [9] found that discharge current, pulse duration and pulse frequency were main significant control parameters for better MRR and surface finish. Trang et al.[10] utilized a neural network to model the WEDM process to assess the optimal cutting parameters.

Literature lacks much to say about the use of WEDM for machining different shape cuts of Al/SiC$_{10\%}$ MMC , so the need has been felt towards the highlighting the process with the goal of achieving mathematical models to select the process parameters for maximum utilization of WEDM with improved process performance.

The present work highlights the development of mathematical models for correlating the inter relationships of various WEDM process parameters to optimize MRR and Ra for triangular, circular, rectangular and all shape combination cuts machining of Al/SiC$_{10\%}$ MMC. This work has been established on the dimensional analysis approach. Mathematical models fitted to the experimental data will contribute towards the selection of the maximum, minimum and optimum process conditions

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## 2 EXPERIMENTAL PROCEDURES

Discontinuous reinforced Al/SiC$_{10\%}$ MMC made up by stir casting route [11],[12] with SiC average particle size 45 µm was used for experimentation. Different sets of 432 machining experiments were performed on SODICK 350W CNC WEDM with MARK 21 controller (Fig.1). The electrode and other machining conditions were selected as follows:

i. Electrode: Brass with 0.25mm in dia.
ii. Specific resistance of die-electric fluid, mA : 1-3
iii. Workpiece height: 5and 10mm
iv. Die electric temperature, $^oC$ : 25-30

Pilot experiments were performed to select test envelope and test points of process parameters for experimental design. These process parameters were listed in Table1 and used in experimental design for the investigation of WEDM process parameters during machining of Al/SiC$_{10\%}$ MMC. All eleven selected independent process parameters were manipulated on WEDM control panel and accordingly 2mm, 4mm and 6mm length triangular, circular and rectangular shape (Fig.2) were machined. During machining cutting speed ($V_{C,}$), gap current (I) and gap voltage (V) were measured from control panel. Surface finish (Ra, µm) was measured by using Surf Test- 300 (Mitituyo make) and the width of cut (b) was measured by using tool makers' microscope. The MRR was calculated [13] as:

MRR = $V_c$ *b * h $mm^3/s$ -----------------------------------(1)

Where, $V_c$ =cutting speed, mm/s,
b=width of cut, mm
h= height of work piece, mm

Fig. 1: Experimental Set Up

Table 1: Process Parameters

| Sr. .No | Machining parameters | Abbre-viation | Selected values | unit |
|---|---|---|---|---|
| i. | Pulse on time | ON | 0.5,2,4,6 | µs |
| ii | Pulse off time | OFF | 12,14, 16,18 | µs |
| iii. | Main power supply peak current | IP | 16,17 | A |
| iv | Servo reference voltage | SV | 90,100, 110, 120 | V |
| v | Servo speed | SS | $6.66*10^{-5}$, $3.33*10^{-5}$, 0.000125, 0.00025 | m/s |
| vi | Wire tension | WT | 12,18 | N |
| vii | Wire speed | WS | 0.083333, 0.116667 0.15 | m/s |
| viii | Dielectric fluid flow | DQ | $8.33333*10^{-5}$ 0.0001166 | $m^3/s$ |
| ix | Al/SiC work-piece thickness | MT | 0.005, 0.01 | m |
| x | Al/SiC work-piece length | ML | 0.002, 0.004, 0.006 | m |
| xi | Al/SiC work-piece cross section | MS | Angular, circular , straight | m |

## 3 Design of Experiments

In this study, 432 experiments were designed on the basis of sequential classical experimental design technique [14] that has been generally proposed for engineering applications. The basic classical plan [15] consists of holding all but one of the independent variables constant and changing this one variable over its range

The main objective of the experiments consists of studying the relationship between 11 independent process parameters with the MRR and Ra dependent responses for triangular, circular, rectangular and all shape cuts combination. Simultaneous changing of all 11 independent parameters was cumbersome and confusing. Hence all 11 independent process parameters were reduced by dimensional analysis. Buckingham's π theorem was adapted to develop dimensionless π terms for reduction of process parameters.

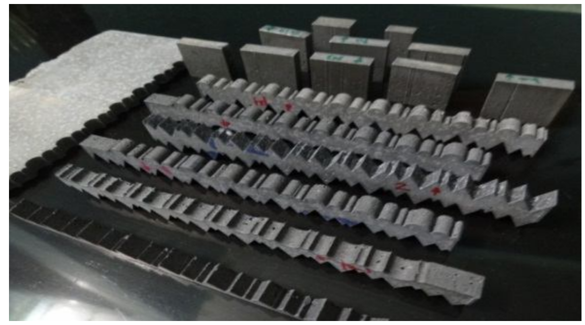

Fig. 2: Machining of Al/ SiC MMC using WEDM

This approach helps to better understand how the change in the levels of any one process parameter of a π terms affects MRR and Ra response for triangular, circular and rectangular shape cut. A combination of the levels of parameters, which lead to maximum, minimum and optimum response, can also be located through this approach. Regression equation models of MRR and Ra were optimized by mini-max principle and LPP.

### 3.1 Formulation of Approximate Generalized Experimental Data Base Model by Dimensional Analysis:

As per dimensional analysis [16], material removal rate (MRR) was written in the function form as :-

$$f_1(ON, OFF, IP, SV, SS, WT, WS, DQ, MT, ML, MS, MRR) = 0 \text{------------(2)}$$

By selecting Mass (M), Length(L), Time (θ) and Current(I) as the basic dimensions, the basic dimensions of the forgoing quantities were:

ON= θ , OFF= θ , IP= I , SV= $L^2M\,\theta^{-3}I^{-1}$ , SS= $L\,\theta^{-1}$,
WT= $ML\,\theta^{-2}$, WS = $L\,\theta^{-1}$, DQ= $L^3\,\theta^{-1}$, MT= L , ML = L
MS= L , MRR= $L^3\,\theta^{-1}$ , SF=L

According to the Buckingham's $\pi$- theorem, (n- m) number of dimensionless groups [16] are forms. In this case n is 12 and m=4, so $\pi_1$ to $\pi_8$ dimensionless groups were formed. By choosing ON, IP, WT, and DQ as a repeating variable, eight π terms were developed as follows:

$$\pi_1 = (ON)^{a_1} * (IP)^{b_1} * (WT)^{c_1} * (DQ)^{d_1} * OFF$$
$$\pi_2 = (ON)^{a_2} * (IP)^{b_2} * (WT)^{c_2} * (DQ)^{d_2} * SV$$
$$\pi_3 = (ON)^{a_3} * (IP)^{b_3} * (WT)^{c_3} * (DQ)^{d_3} * SS$$
$$\pi_4 = (ON)^{a_4} * (IP)^{b_4} * (WT)^{c_4} * (DQ)^{d_4} * WS$$
$$\pi_5 = (ON)^{a_5} * (IP)^{b_5} * (WT)^{c_5} * (DQ)^{d_5} * MT$$
$$\pi_6 = (ON)^{a_6} * (IP)^{b_6} * (WT)^{c_6} * (DQ)^{d_6} * ML$$
$$\pi_7 = (ON)^{a_7} * (IP)^{b_7} * (WT)^{c_7} * (DQ)^{d_7} * MS$$
$$\pi_8 = (ON)^{a_8} * (IP)^{b_8} * (WT)^{c_8} * (DQ)^{d_8} * MRR$$

By substituting the dimensions of each quantity and equating above π terms to zero and using dimensional analysis method equation 2 becomes,

$$0 = f_1(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8) \text{--------------------(3)}$$

Since $5^{th}$, $6^{th}$ &7 π term had same denominator.

Hence,

$0 = f_1(\pi_1, \pi_2, \pi_3, \pi_4, \pi'_5, \pi_8)$ ------------------------------(4)

$\pi_8 = f_1(\pi_1, \pi_2, \pi_3, \pi_4, \pi'_5)$ ------------------------------------(5)

Where,

$\pi_1$=(OFF/ON);

$\pi_2$= ((ON$^{2/3}$ * IP * SV) / (DQ$^{1/3}$ *WT));

$\pi_3$= ((ON$^{2/3}$ * SS) / (DQ$^{1/3}$));

$\pi_4$=((ON$^{2/3}$ * WS) / (DQ$^{1/3}$));

$\pi'_5$ =(( MT* ML * MS) / (ON$^{2/3}$ *DQ$^{1/3}$));

$\pi_8$ =((MRR) / (DQ))

Hence dimensional analysis was reduced 12 independent and dependent variables into only six dimensionless π terms.
Similarly, dimensionless π terms for surface finish (Ra) were found by dimensional analysis,

$\pi_9 = f_1(\pi_1, \pi_2, \pi_3, \pi_4, \pi'_5)$---------------------------------(6)

and

$\pi_9$ = (( Ra) / (ON$^{2/3}$ *DQ$^{1/3}$))

The relationship between various parameters was unknown. The dependent parameter i.e. $\pi_8$ $\pi_9$ relating to MRR and Ra were bear an intricate relationship with remaining $(\pi_1, \pi_2, \pi_3, \pi_4, \pi'_5)$ terms evaluated on the basis of experimentation. The true relationship is difficult to obtain.
The possible relation may be linear, log linear, polynomial with n degrees, linear with products of independent $\pi_i$ terms. In this manner any complicated relationship can be evaluated and further investigated for error. Hence the relationship for MRR was formulated as:

$\pi_8 = k_0 * (\pi_1)^{k_1} * (\pi_2)^{k_2} * (\pi_3)^{k_3} * - - * (\pi_5)^{k_5}$-------------(7)

Equation is modified as:

$\pi_8 = (e)^{k_0} * (\pi_1)^{k_1} * (\pi_2)^{k_2} * (\pi_3)^{k_3} * - * (\pi_5)^{k_5}$

Obtaining log on both sides we get,

$\log\pi_8 = \log kk_0 * k_1\log(\pi_1) * k_2\log(\pi_2) * k_3\log(\pi_3) * k_4\log(\pi_4) * k_5\log(\pi_5)$ ------------------------------------------(8)

This linear relationship now can be viewed as the hyper plane in five dimensional spaces. To simplify further let us replace log terms by capital alphabet terms implies,

$P_8 = k_0 + k_1A + k_2B + k_3C + k_4D + k_5E$

$P_9 = k_0 + k_1A + k_2B + k_3C + k_4D + k_5E$

This is true linear relationship between A to K to reveal $P_8$ and $P_9$ i. e. log MRR and Log Ra.
Applying the theories of regression analysis [16], the aim is to minimize the error
Error (E) = Ye - Yc
Yc is the computed value of $p_8$ using regression equation and Ye is the value of the same term obtained from experimental data with exactly the same values of $p_1$ ---- $p_5$.
Correlation and reliability were computed for model accuracy.

### 3.2 Mathematical Model for MRR

The multiple linear regression equations of MRR were found as :
For all shape cuts combination products:
Log10, $\pi_8$ =
-1.7048 - 0.0885A - 0.1126B + 0.3751C -0.0385D + 0.2682E
For triangular shape cut product P1 :
Log10, $\pi_8$ =
-3.5208 - 0.2485A + 0.4106B + 0.3311C - 0.5729D + 0.2702E
For circular shape cuts product P2:
Log10, $\pi_8$ =
-0.4931 -.1195A - 0.4600B + 0.4312C + 0.1184D + 0.3509E
For rectangular shape cuts product P3:
Log10, $\pi_8$ =
-2.7889 - 0.3092 A + 0.0721B + 0.3698C - 0.3838D + 0.2466E

### 3.3 Mathematical Model for Ra

The multiple linear regression equations of Ra were found as :
For all shape cuts combination products:
Log10, $\pi_9$ =
-1.6399 + 0.3317 A -0.0946 B+ 0.1438 C+ 0.0009D - 0.0030E
For triangular shape cut product P1 :
Log10, $\pi_9$ =
-2.1102 + 0.3288 A + 0.0760 B + 0.1181C - 0.1196 D + 0.0092E
For circular shape cuts product P2:
Log10, $\pi_9$ =
-1.3866 + 0.2971 A - 0.2025 B + 0.1671C + 0.0257D + 0.0014E
For rectangular shape cuts product P3:
Log10, $\pi_9$ =
-1.5496 + 0.3181A - 0.1545B + 0.1345C + 0.0332D + 0.0092E
The comparative RMS error , corelation and reliability was computed for all multiple regression models of MRR and Ra asgiven in Table 2.

Table2: Comparative RMS error, correlation and Reliability Values of models

| | | RMS error | correlation | Reliability |
|---|---|---|---|---|
| MRR | all shape | 0.2820 | 0.5138 | 77.2980 |
| | triangular | 0.2821 | 0.5610 | 77.8143 |
| | circular | 0.2630 | 0.5787 | 78.2539 |
| | Rectangular | 0.2855 | 0.5458 | 77.6251 |
| Ra | all shape | 0.0836 | 0.8045 | 93.3187 |
| | triangular | 0.0842 | 0.7897 | 93.3816 |
| | circular | 0.0741 | 0.8474 | 94.0694 |
| | Rectangular | 0.0877 | 0.7954 | 92.8459 |

### 3.4 Process Parameters Selection by Mini-Max Principle

From above mathematical models the obvious aim was to maximize the MRR and minimize Ra values for all three shape cuts and all shape cuts combination. Studies revealed the range of variation for every input parameter. The most satisfying value on this range for such a parameter was achieved using range bound mini-max principle of optimization. The corresponding minimum and maximum values of π term were given in Table3. The MRR was maximizes by using Mini-max principle while Ra was mini-

mizes by using Maxi-min principle.
The corresponding pi term parameters to maximize MRR by mini-max principle were as follows :
For all shape cuts combination:

$$A_a\ B_a\ C_b\ D_a\ E_b = -4.66602$$

For triangular shape cuts Product P1:

$$A_a\ B_b\ C_b\ D_a\ E_b = -4.23159$$

For circular shape cuts product P2:

$$A_a\ B_a\ C_b\ D_b\ E_b = -4.267801$$

For rectangular shape cuts product P3:

$$A_a\ B_b\ C_b\ D_a\ E_b = -4.43431$$

Table 3 : Min and Max values of pi terms

| Sr. no. | π term | MRR and Ra a | MRR and Ra b |
|---|---|---|---|
| 1 | A | 0.30103 | 1.447158 |
| 2 | B | -0.98658 | 0.108944 |
| 3 | C | -7.36679 | -5.72357 |
| 4 | D | -3.96885 | -2.94541 |
| 5 | E | -4.8041 | -3.92082 |

*$A_a$ =minimum value of A
*$A_b$ = maximum value of A

The corresponding pi term parameters to minimize Ra by maxi-min principle were as follows :
For all shape cuts combination:

$$A_a\ B_b\ C_a\ D_a\ E_b = -2.601508$$

For triangular shape cuts Product P1:

$$A_a\ B_a\ C_a\ D_b\ E_a = -2.64814$$

For circular shape cuts product P2:

$$A_a\ B_b\ C_a\ D_a\ E_a = -2.65894$$

For rectangular shape cuts product P3:

$$A_a\ B_b\ C_a\ D_a\ E_a = -2.6374$$

Above results had shown model adequacy about maximum MRR and Minimum Ra values.

### 3.5 Optimization

Optimization of machining characteristics of Al/ $SiC_{10\%}$ MMC in WEDM is to search an optimal solution for a given objectives satisfying the required constraints. The objective was to maximize the MRR for different shape cuts of machining with the constraints involved were bound values of π terms and minimum Ra. This adds to the complexities of the problem. Linear programming [ ] is a strong tool to optimize where the objective function and the constraints are linear. Based on the computed results, LPP model was formulated.
The LPP model for MRR ( all shape cuts combination): objective function,
Log10, MRR =
-1.7048 - 0.0885A - 0.1126B + 0.3751C - 0.0385D + 0.2682E
Subject to constraints,
-1.6399 + 0.3317 A -0.0946 B+ 0.1438 C+ 0.0009D -0.0030E >= -2.601508;
i.e. Ra >= -2.601508; and
0.30103 <=(Log10,A) <= 1.447158;
-0.98658 <=(Log10,B) <= -0.108944;
-7.36679 <=(Log10,C) <=- -5.72357;
-3.96885 <=(Log10,D) <=- -2.94541;
-4.8041 <=(Log10,E) <= -3.92082

With similar approach, objective function and constraints were developed for product P1, P2 and P3 to optimize MRR with constraints of Ra and A,B,C,D and E parameters.
The optimum conditions were obtained by using MS excel - Solver as follows:
$A_a\ B_b\ C_a\ D_a\ E_a$
And the values were calculated as per Table 4.

Table 4 : Optimized values of MRR for all product.

| Sr. no. | unit | all shape cuts | product P1 | product P2 | product P3 |
|---|---|---|---|---|---|
| | K | -1.7048 | -3.5208 | -0.4931 | -2.7889 |
| 1 | A | 0.30103 | 0.30103 | 0.30103 | 0.30103 |
| 2 | B | 0.108944 | 0.108944 | 0.108944 | 0.108944 |
| 3 | C | -7.36679 | -7.36679 | -7.36679 | -7.36679 |
| 4 | D | -3.96885 | -3.96885 | -3.96885 | -3.96885 |
| 5 | E | -4.8041 | -4.8041 | -4.8041 | -4.8041 |
| Optimum MRR | | -5.64265 | -5.01433 | -5.91141 | -5.25980 |
| Optimum Ra | | -2.59885 | -2.44248 | -2.65894 | -2.637471 |

## 4 Results and Discussion

### 4.1 Development of π Terms

The Buckingham's 'π' theorem was formulated six dimensionless π terms and each π term was given the importance of each dimensionless group. The first π term implied the effect of spark frequency of wire EDM process on MRR and Ra values. The second π term was shown the importance of spark energy supplied to the wire so as to minimize the breakage of wire which has taken a major non-productive time during WEDM. Third, fourth and fifth π terms were relate with the role of servo speed, wire speed and product variability during machining. Finally the last π term reflected the output MRR and Ra effect.

### 4.2 Effect of working parameters on the volumetric metal removal rate

Dimensional analysis was suggested to keep $\pi_1$ term as low as possible because high sparking frequency gives better MRR values for all shape cuts, triangular, circular and rectangular shape products.

Dimensional analysis observed that $\pi_2$ term to keep less for all shape cuts combination and circular shape cut product while for triangular and rectangular shape cut product $\pi_2$ must be high. This indicated that circular shape and all shape cuts combination machining demanding lesser spark energy for higher MRR. It is also reduced the wire breakage and hence helpful to minimize non-productive time.

Servo speed $\pi_3$ term was always kept higher so as to maximize MRR for all shapes cut and combination of all. It is major parameter to concentrate to maximize the MRR but need to take care of wire breakage.

The wire speed $\pi_4$ term was keep small to give higher MRR for all shape combination cuts, triangular and rectangular shape cuts but was less for circular shape cut. it is generally observed that more wire breakage for circular shape cuts if wire speed is more.

Product variability $\pi^!_5$ term was always keep high for all shape cuts and combination of all shape cuts. It explicitly suggested that if larger volume is provided then MRR is high with all above process parameters combinations.

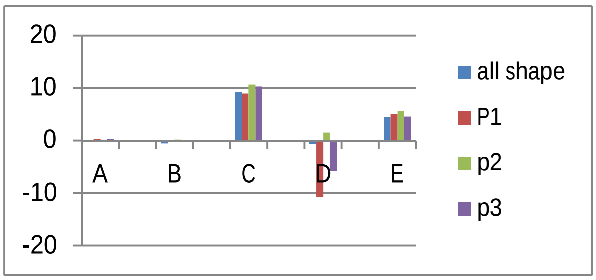


Fig. 3: Sensitivity analysis of MRR

The sensitivity analysis(Fig.3) proved that the higher levels of servo speed ( $\pi_3$) term and product variability ($\pi^!_5$) term are more sensitive for the increase in MRR for all shape cuts , triangular , circular and rectangular shape cut products. while lower levels of wire speed ($\pi_4$) term is similarly sensitive for reduction of MRR for triangular and rectangular shape but low sensitive in all shape cuts. The same term also shown higher level was more sensitive for circular shape cut.

### 4.3 .Effect of working parameters on surface roughness

From the dimensional analysis, surface roughness was improved by minimizing $\pi_1$ and $\pi_3$ terms for triangular, circular, rectangular and all three shape cuts combination. The $\pi_1$ term was given ON and OFF pulse time effect on Ra values. The term can be manipulated by changing any one parameter of the group. This change improves the frequency of pulse supply and has support improvement into Ra.

While $\pi_2, \pi_4, \pi^!_5$ terms was not shown any unidirectional effect on improvement in Ra values as the shape of cuts changes. Minimum $\pi_2$ term has given better Ra value for triangular shape cut product and maximum $\pi_2$ term for circular, rectangular and all shape cuts combination.

Minimum $\pi_4$ improved the Ra for circular, rectangular shape product and all shape cuts combination. While maximum $\pi_4$ was given better results for triangular shape cut product P1.

Minimum Product variability $\pi^!_5$ term had shown the improvement in Ra values for triangular, circular and rectangular shape product and maximum $\pi^!_5$ for all shape cuts combinations.

Sensitivity analysis(Fig.4) implied that the lower levels of off/on ($\pi_1$) term were more sensitive for better Ra values while higher values of servo speed ($\pi_3$) term were highest sensitive but affect on Ra values for all shape cuts, triangular, circular and rectangular cut products. The spark energy($\pi_4$) shown lower sensitivity but improves values in triangular shape cuts only while for all shape , circular and rectangular shape cut recued the Ra values. and product variability ($\pi^!_5$) terms very less sensitive for shapes products.

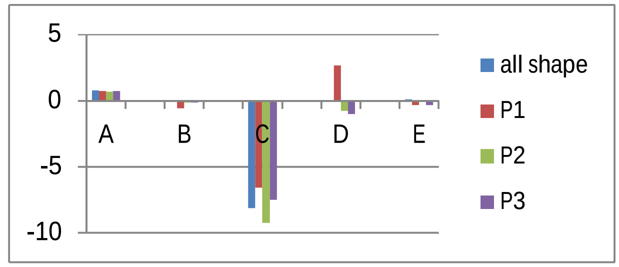


Fig. 4: Sensitivity analysis of Ra

### 4.4 Optimization of Process Parameter

The process parameters computation for maximum MRR and Minimum Ra always was conflicting with each other and industries always wants optimum of both so that can satisfy the industrial requirements. This is achieved by LPP with minimum Ra values (Table 4) and upper and lower bound process parameter constraints. The solution of LPP suggested maximum electrical energy supply( $\pi_2$) term and all other minimum $\pi$ term provides the optimum solution for optimized MRR and Ra values for triangular, circular, rectangular shape products and all shape cuts combinations.

## 5 Conclusion:

1. WEDM process has proved its adequacy to machine Al/SiC$_{10\%}$ MMC under acceptable volumetric material removal rate which is reached upto--- and surface finish less than microns.
2. The dimensionless $\pi$ terms have provided the idea about combined effect of process parameters in that $\pi$ terms. A simple change in one process parameter in the group helps the manufacturer to maintain the required MRR and Ra values so that the productivity is increased
3. The mathematical models developed with dimensional analysis for different shape cuts for predicting the characteristics of Wire electric discharge machining can be effectively utilized for machining of Al/Sic$_{10\%}$ MMCs in wide spread applications.
4. The computed selection of WEDM process parameters by dimensional analysis provides effective guidelines to the manufacturing engineers so that they can maximize Al/SiC$_{10\%}$ MMC utilization for industrial applications for higher machining performances.

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