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# Taguchi Optimization of Wire EDM Parameters for Surface Roughness of Al 6061 Alloy Based Composite With Sic Reinforcement

**Rohit Sharma, Vivek Aggarwal, H. S. Payal**

***Abstract*****: *The Al 6061 alloy based Al- SiC metal matrix composite is rated as one of the most commonly used Metal Matrix Composites (MMCs) today. The MMC specimens studied in this research work were fabricated with the stir casting process. This research work studies important parameters in the wire electric discharge machining of Al-SiC 6061 MMC. We employed Taguchi approach to study the machining parameters during the machining process and to minimize the surface roughness values of the surfaces obtained by Wire EDM (Wire Electric Discharge Machine) machining. We found out that out of the seven factors used in this study, gap voltage during the wire EDM machining is the most prominent factor which influences the obtained surface roughness values. Comparatively, a very low value of surface roughness (Rq) was obtained by us during confirmation test by us.***

***Keywords*** **: *Wire Electric Discharge Machining, MMCs, Al SiC, 6061, Composite, Roughness, Orthogonal Arrays, Taguchi.***

## I. INTRODUCTION

There are a total of seven main factors that influence the surface roughness value of a surface during the machining done by Wire EDM process. These factors have been studied in this research work by us, six out of which are namely the nozzle workpiece distance, the wire feed rate at which the machining wire approaches the workpiece in order to machine it, the machining current which is made to pass through the wire and workpiece gap, the gap voltage generated between the wire and the workpiece, the wire tension of the machining wire, and the dielectric flow rate at which the dielectric is incident upon the machined area of the workpiece from the upper nozzle. Amongst these six factors, the first two factors have been studied by us at two levels and the remaining four factors have been studied at four levels each. The Al SiC 6061 MMC that we have used in this work is a metal matrix composite (MMC) in which SiC particles have been used as a reinforcement phase. We also studied the percentage of SiC particles at two levels of 5% and 10% SiC as the work piece composition, totaling the number of factors studied as seven.

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Design of experiments in this work has been done by us in accordance with the Taguchi technique which makes use of Orthogonal Arrays.
We found out the most favorable levels of each of the seven factors. Confirmatory test results have been conducted and the analysis of results has also been done by us.

### *1.1 Metal matrix composites AlSiC 6061*

Metal matrix composites (MMCs) generally consist of lightweight metal alloys of aluminum, magnesium, or titanium, reinforced with ceramic particulate, whiskers, or fibers. The reinforcement is very important in an MMC because it determines its mechanical properties, cost, and performance. Compared with the unreinforced metal, MMCs have significantly greater stiffness and strength. However, these properties are obtained at the cost of lower ductility and toughness.
The aluminum industry has evolved over the past 100 years (i.e. year 1900 onwards) from the limited production of alloys and products to the high-volume manufacturing of a wide variety of products. Later, the introduction of alloy aluminum 6061 (also known as 61S) in 1935 filled the need for medium-strength, heat-treatable products with good corrosion resistance which could be welded or anodized. 6061 components can be easily fabricated by extrusion, rolling, or forging. Structural sheets and tooling plates produced for the flat-rolled products market, extruded structural shapes, rods, bars, tubings, automotive drive shafts, and aircraft structures are manufactured from alloy 6061.
The Al SiC 6061 Metal Matrix Composite (MMC) used in this research work has the alloy of aluminum 6061 as its matrix phase and particles of SiC with 220 mesh size as its reinforcement phase. The two variations studied by us in this work are those of 5% SiC and of 10% SiC compositions, respectively. The specimens used in this work had been prepared by us with the stir casting process.

### *1.2 The Wire EDM*

Since a long time ago, researchers have attempted to employ non conventional machining process such as EDM, WEDM (Wire EDM), and AWJM (Abrasive Water Jet Machining) which are used for machining hard and high strength alloys [1]. The origin of electrical discharge machining goes back to 1770 when English scientist Joseph Priestly discovered the erosive effect of electrical discharges on metals [2]. In a Wire Electrical Discharge Machining (WEDM), the tool electrode is a continuously moving conductive wire over an electrically conducting workpiece. The practical technology of the WEDM process is based on the conventional EDM sparking phenomenon utilizing the widely accepted non contact technique of material removal.

Functions like wire feed, table movement, dielectric circulation, and power can all be controlled through a keyboard.

The mechanism of metal removal in Wire Electrical Discharge Machining involves the complex erosion effect from electric sparks generated by a pulsating direct current supply generated between the conductive wire and the work piece. Water is usually used as a dielectric in WEDM. Water is advantageous as a dielectric in this process because of its less viscosity and rapid cooling rate.

The wire EDM machine used for this work was Electra Supercut 734. This machine uses a brass wire of diameter 0.2 mm as cutting wire and deionized water as dielectric which is continuously circulated through the machine and filtration unit in a closed circuit. Its block diagram representation has been given in Figure 1.

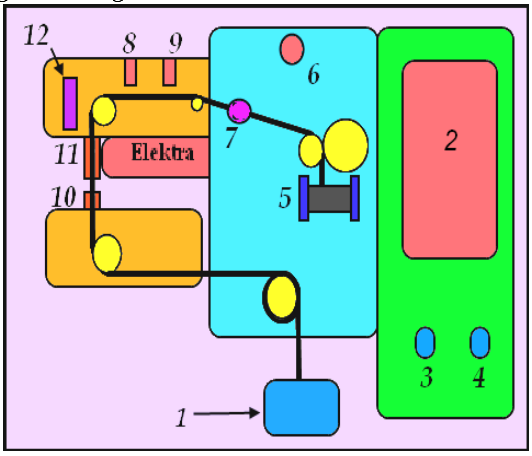


**Fig. 1: The block diagram of Wire EDM machine used for this study.**

Here, the wire gets supplied from part labeled 5, the wire spool, its tension gets regulated by arrangement 7, moves through the upper nozzle 11 and lower nozzle 10, and finally gets collected in bin 1. 2 is panel which shows various displays and dials. 3, 4, and 6 are various meters like ammeter and voltmeter. 8 and 9 are used to control upper and lower nozzle flow rates, and 12 is used to adjust the upper nozzle workpiece gap.

## II. PREPARATION OF SPECIMENS

Aluminum 6061 is a precipitate-hardened aluminum alloy containing magnesium and silicon as its major alloying elements [3]. The different types of ceramics materials used in reinforcement are carbides (B4C, SiC, and TiC), oxides (Al2O3, SiO2) and nitrides (AlN, Si3N4) [4]. In this work, alloy aluminum 6061 was taken as the matrix and SiC was taken as the reinforcement material in order to prepare the 6061 Al-SiC MMC. To start with, in order to confirm the composition of the aluminum 6061 alloy, we carried out its spectrometry test as per the ASTM E1251-2011 test method. Two square prisms had been cut by us from the alloy piece for this purpose on a wire EDM machine, as have been depicted in Figure 2.


**Fig.2. We took two square prisms from the aluminum 6061 alloy piece in order to carry out spectrometry analysis.**

The results were tallied by us with the available data of Al SiC alloy's chemical composition, after which, this alloy piece was used for preparation of Al SiC specimens by the stir casting process. The results of this test have been shown in Table 1.

**Table 1. Spectrometry test results of alloy aluminum 6061**

| **Element** | **Cu** | **Mg** | **Si** | **Fe** | **Ni** | **Mn** |
|---|---|---|---|---|---|---|
| Value (%) | 0.2030 | 0.9330 | 0.7840 | 0.3040 | 0.0032 | 0.0836 |
| **Element** | **Zn** | **Pb** | **Sn** | **Ti** | **Cr** | **Al** |
| Value (%) | 0.0561 | 0.0270 | < 0.0100 | 0.0689 | 0.0472 | *Rem.* |

In the specimen preparation stage, the aluminum 6061 alloy piece which was taken as the matrix phase was cut into smaller blocks by us so as to facilitate melting in a vertical muffle furnace. SiC powder of 220 mesh size had been taken by us as the reinforcement phase. We accurately weighed both of them for the 5% and 10% composition specimens respectively. We also added a magnesium ribbon strip which had been 1% by weight of alloy. The aluminum 6061 blocks, the SiC powder, and the magnesium wire used for the preparation of specimens have been shown in Figure 3.

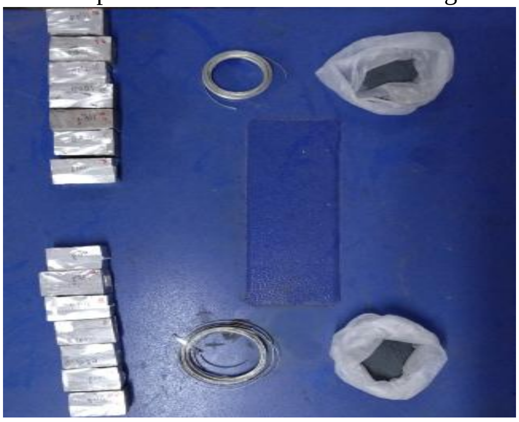

**Fig. 3. The ingredients for making the specimens which were used in this study. The aluminum 6061 blocks, the magnesium wire, and the 220 mesh size SiC particles have been placed left to right, in their respective order.**

Stir Casting is a liquid state method of composite materials fabrication in which a dispersed phase (ceramic particles, short fibers) is mixed with a molten matrix metal by means of mechanical stirring. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional technologies [5]. During casting, the accurately weighed aluminum 6061 blocks were placed in a crucible by us. We then placed this crucible in an electrical vertical muffle furnace. As a matter of fact, stir casting furnace using electrical energy is the most common, and among that, electrical resistance is the most frequently used technique [6]. We then preheated the crucible to a temperature of about $850^0$C. Preheating of reinforcement results in uniform distribution and better mechanical properties [7]. The preheated SiC particles were then added to this crucible by us. SiC particles are preheated in this process so as to expel moisture and other volatile contaminants from them. Then the addition of an accurately weighed quantity of magnesium ribbon to the hot crucible was done by us which was slightly problematic as it caught fire on incident to furnace heat but was immediately sunk in the molten slurry with an m.s. rod (the operators had previous experience of doing so, hence were well prepared beforehand). In order to prevent the SiC particles from settling at the bottom and to keep them suspended in the molten slurry, an electrical motor operated stirrer of graphite was left to rotate in it for some time by us, as shown in Figure 4.

**Fig. 4. A stirrer of graphite was used by us to rotate the liquefied contents of the crucible placed in the furnace.**

We then poured the molten metal into two specially prepared cylinder molds. These cylindrical molds were made of metal and were embedded in casting sand, as shown in Figure 5.

**Fig. 5. Some slag that had been floating on the molten metal was removed with an m.s. rod, and the remaining molten metal was poured in specially made cylinder molds by us.**

After allowing to cool down and solidify for some time, we removed the first solidified casting from its cylinder mold The process was repeated by us for the other casting, giving two castings, the one with 5% SiC content composition and the other one with 10% SiC content composition, respectively. The surfaces of these castings were pitted and had been having inaccurate dimensions at that time. Hence, they were turned by us on a lathe. These specimens have been shown in Figure 6.

**Fig. 6.The two castings after being turned to accurate dimensions of 14 mm diameter.**

We carried out the SEM analysis of one of these specimens on a Scanning Electron Microscope of JEOL make whose results have been shown in Figure 7.

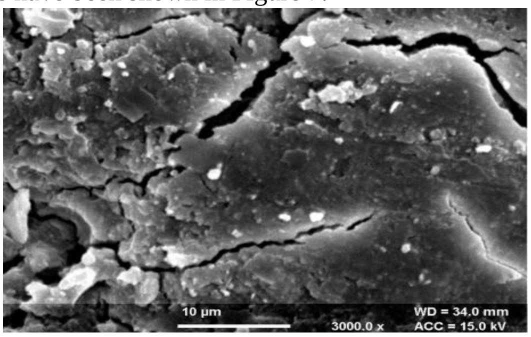


**Fig. 7. SEM photograph of the specimen obtained by stir casting process.**

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## III. DESIGN OF EXPERIMENTS

An experimental design should satisfy two objectives. Firstly, the number of trials should be minimum, and secondly, conditions of each trial must be specified. Taguchi design of experiments is one such type of experimental design. It is an efficient test strategy that possesses some advantages because of a balanced arrangement.

### *1.1. The Taguchi technique and the Orthogonal arrays*

The Taguchi technique makes use of Orthogonal Arrays (OAs). An OA is a mathematical invention recorded by Jacques Hadamard, a French mathematician in as early as 1897. It is known that Taguchi developed his catalog of orthogonal arrays from mathematical procedures published in well-known English language journals [8]. The use of Latin squares Orthogonal Arrays (a type of Orthogonal Array) for experimental design however dates back to the time of World War II. The Taguchi technique of layout of the conditions (Design of Experiments) involves many factors at a time. This is a statistical technique which was first proposed by an Englishman named Sir RA Fischer in the 1920s. This method is popularly known as the Factorial Design of Experiments. Factorial Design of Experiments may either be called a *Full* Factorial Design or else a *Fractional* Factorial Design. A Full Factorial Design identifies all possible combinations for a given set of factors. In a Full Factorial Design, seven factors, each at two levels needs $2^7$ = 128 experiments. In order to reduce such a large number of experiments to a practical level, only a small portion from all the possibilities is selected in the Fractional Factorial Design. This is done by making use of Orthogonal Arrays. An Orthogonal Matrix Array, also called the Orthogonal Array, abbreviated as OA is defined as such a Fractional Factorial Matrix that it assumes a balanced, fair comparison of levels of any factor in which all columns can be evaluated independently of one another.

The term levels of various factors is defined as the setting or values of various factors in a factorial experiment. Generally, level 1 is kept lesser in numerical value than level 2. It is also to be taken care of that both levels of a factor should have the same units. It can be seen that Taguchi method has been successfully used in the optimization of machining parameters. In fact, optimization of process parameters is the key step in the Taguchi method in achieving high quality without increasing the cost. The wedding of a style of experiments with optimization of management parameters to get best effects is completed within the Taguchi approach [9].

## IV. CONDUCTING THE EXPERIMENTS

After the design of experiments, when each experimental run was decided in terms of various parameters and their levels, we mounted the specimens on the wire EDM machine and performed machining cuts which were 48 in number. We performed them in accordance to the conditions described by the l-16 orthogonal array. Each of these cuts was 14 mm deep, and all these cuts were placed mutually at an axial distance of 2.5 mm. The machining of such cuts on cylindrical specimens resulted in semi circular shaped pieces, one of which is shown in Figure 8.

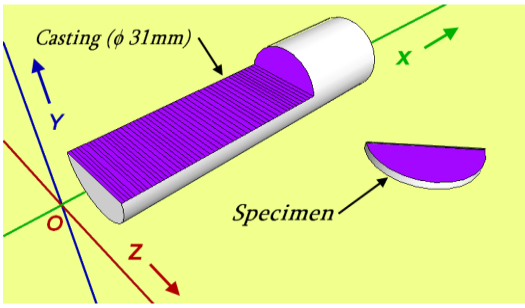


**Fig. 8. The three dimensional model of specimen which were machined out of a casting. The purple color shows the surfaces machined out by the wire EDM process. Forty eight such specimens have been cut at different variable settings.**

During experimentation, after machining each cut, we changed the machining parameter levels every time as per the Taguchi design of experiments and then machined the next cut on the specimen. We machined all the cuts on both the specimens as per the design of experiments. After that, surface roughness testing was carried out by us on the surfaces brought out by the machining cuts.

As shown in Figure 9 below, during the surface roughness testing, the actual surface (line) of each surface was measured with reference to the mean line with a diamond tipped stylus and the roughness values were given by the measurement instrument.

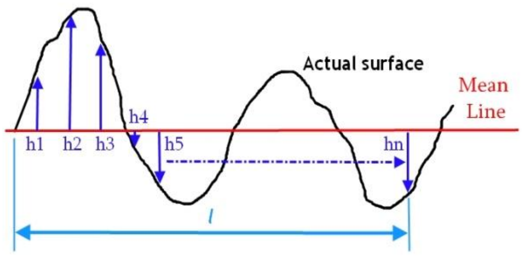


**Fig. 9. Actual surface in relation to the mean line of the surface for surface measurement purpose.**

In order to get more accurate results, we carried out surface roughness measurement at five places on each machined surface and then considered their average values. A Mitutoyo make surftest meter SJ-201-P was used for this purpose, and roughness of machined surfaces was measured in units of µm on the scale of $R_q$ by us. This is depicted in Figure 10 below. Rq (root mean square) has earlier been considered and referred to as an amplitude parameter by Pirva, Tudor, and Gavrus in context of surface micro topography [10].

**Fig. 10. Photograph of the roughness testing of one of the semi circular shaped pieces being carried out.**

The Taguchi l-16 orthogonal array that we have used in this work directs to use 16 experimental trials. For the sake of accuracy, each of these tests had been performed three times by us. Because of that, the total number of tests came out to be 48. This was done by us in accordance to the concept of repetition. After obtaining the surface roughness values of 48 semi circular pieces, we found out the average surface roughness obtained during machining at each of the 16 settings of the orthogonal array by taking average. These are the 16 settings that had been directed by the l-16 orthogonal array in accordance to which these 48 tests had been performed by us. Table 2 shows these 16 values that we next used in the orthogonal array.

**Table 2. Average surface roughness obtained during machining at each setting of Orthogonal Array (numbered 1 to 16)**

| *Number of cut* | Surface roughness values of specimen pieces (numbered 1 to 16) *(μm)* | Surface roughness values of specimen pieces (numbered 17 to 32) *(μm)* | Surface roughness values of specimen pieces (numbered 33 to 48) *(μm)* | Average surface roughness (OA settings of 1 to 16) (μm) |
|---|---|---|---|---|
| 1 | 6.78 | 4.87 | 4.85 | 5.5 |
| 2 | 4.2 | 5.88 | 4.93 | 5 |
| 3 | 6.75 | 7.47 | 6.26 | 6.83 |
| 4 | 6.48 | 8.33 | 8.58 | 7.8 |
| 5 | 4.86 | 4.61 | 4.45 | 4.64 |
| 6 | 3.97 | 6.17 | 4.09 | 4.74 |
| 7 | 4.53 | 5.32 | 4.66 | 4.84 |
| 8 | 8.09 | 6.66 | 6.21 | 6.99 |
| 9 | 4.96 | 5.4 | 3.76 | 4.71 |
| 10 | 7.5 | 4.59 | 4.15 | 5.41 |
| 11 | 4.54 | 6.82 | 5.02 | 5.46 |
| 12 | 7.23 | 6.6 | 7.27 | 7.03 |
| 13 | 4.51 | 4.05 | 4.53 | 4.36 |
| 14 | 5.8 | 4.48 | 4.25 | 4.84 |
| 15 | 5.15 | 4.83 | 3.91 | 4.63 |
| 16 | 7.71 | 6.12 | 4.89 | 6.24 |

As per the standard method of Taguchi analysis of orthogonal arrays, we placed these 16 values on the right side of the l-16 orthogonal array (in yellow colored blocks for better comprehension) as shown in Table 3.

**Table 3. Orthogonal Array l-16 for surface roughness.**

| | | *Level 1* | *Level 2* | *Level 3* | *Level 4* |
|---|---|---|---|---|---|
| *Factor A* | *Work piece composition* | *5 % SiC* | *10 % SiC* | | |
| *Factor B* | *Nozzle workpiece distance* | *40 mm* | *50 mm* | | |
| *Factor C* | *Wire feed rate* | *3 m/min* | *5 m/min* | | |
| *Factor D* | *Machining Current* | *0.50 A* | *0.75 A* | *1.00 A* | *1.25 A* |
| *Factor E* | *Gap voltage* | *60 V* | *64 V* | *68 V* | *72 V* |
| *Factor F* | *Wire tension* | *900 g* | *1000 g* | *1100 g* | *1200 g* |
| *Factor G* | *Dielectric flow rate* | *1.0 l.p.m.* | *1.5 l.p.m.* | *2.0 l.p.m.* | *2.5 l.p.m.* |

| *Exp. trial no.* | *Factor A* | *Factor B* | *Factor C* | *Factor D* | *Factor E* | *Factor F* | *Factor G* | *(μm) surface roughnessAverage* |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 5.5 |
| 2 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 5 |
| 3 | 2 | 1 | 2 | 1 | 3 | 3 | 3 | 6.83 |
| 4 | 2 | 2 | 1 | 1 | 4 | 4 | 4 | 7.8 |
| 5 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 4.64 |
| 6 | 2 | 1 | 2 | 2 | 2 | 1 | 2 | 4.74 |
| 7 | 1 | 2 | 2 | 2 | 3 | 4 | 4 | 4.84 |
| 8 | 1 | 1 | 1 | 2 | 4 | 3 | 3 | 6.99 |
| 9 | 1 | 2 | 2 | 3 | 1 | 3 | 4 | 4.71 |
| 10 | 1 | 1 | 1 | 3 | 2 | 4 | 3 | 5.41 |
| 11 | 2 | 2 | 1 | 3 | 3 | 1 | 2 | 5.46 |
| 12 | 2 | 1 | 2 | 3 | 4 | 2 | 1 | 7.03 |
| 13 | 2 | 1 | 2 | 4 | 1 | 4 | 2 | 4.36 |
| 14 | 2 | 2 | 1 | 4 | 2 | 3 | 1 | 4.84 |
| 15 | 1 | 1 | 1 | 4 | 3 | 2 | 4 | 4.63 |
| 16 | 1 | 2 | 2 | 4 | 4 | 1 | 3 | 6.24 |

## V. ANALYSIS OF RESULT

### *5.1. Calculations for the Average Effects of surface roughness*

The calculations of the Average Effects of various parameters affecting surface roughness have been shown below at various levels.

The Average Effects of Work piece composition,

$A_1$= (5.5+5+4.84+6.99+4.71+5.41+4.63+6.24)/8 =5.415,

$A_2$= (6.83+7.8+4.64+4.74+5.46+7.03+4.36+4.84)/8 =5.713.

The Average Effects of Nozzle workpiece distance,

$B_1$= 5.5+6.83+4.74+6.99+5.41+7.03+4.36+4.63)/8 = 5.686,

$B_2$= (5+7.8+4.64+4.84+4.71+5.46+4.84+6.24)/8 = 5.441.

The Average Effects of Wire feed rate,

$C_1$= (5.5+7.8+4.64+6.99+5.41+5.46+4.84+4.63)/8 = 5.659,

$C_2$= (5+6.83+4.74+4.84+4.71+7.03+4.36+6.24)/8 = 5.469.

The Average Effects of Machining Current,

$D_1$ = (5.5+5+6.83+7.8)/4 = 6.282,

$D_2$= (4.64+4.74+4.84+6.99)/4 = 5.303,

$D_3$= (4.71+5.41+5.46+7.03)/4 = 5.653,

$D_4$= (4.36+4.84+4.63+6.24)/4 = 5.018.

The Average Effects of Gap voltage,

$E_1$= (5.5+4.64+4.71+4.36)/4 = 4.803,

$E_2$ = (5+4.74+5.41+4.84)/4 = 4.998,

$E_3$= (6.83+6.84+5.46+4.63)/4 = 5.440,

$E_4$= (7.8+6.99+7.03+6.24)/4 = 7.015.

The Average Effects of Wire tension,

$F_1$= (5.5+4.74+5.46+6.24)/4 = 5.485,

$F_2$ = (5+4.64+7.03+4.63)/4 = 5.325,

$F_3$ = (6.83+6.99+4.71+4.84)/4 = 5.843,

$F_4$= (7.8+4.84+5.41+4.36)/4 = 5.603.

The Average Effects of Dielectric flow rate,

$G_1$= (5.5+4.64+7.03+4.84)/4 = 5.503,

$G_2$= (5 +4.74+5.46+4.36)/4 = 4.890,

$G_3$= (6.83+6.99+5.41+6.24)/4 = 6.368,

$G_4$= (7.8+4.84+4.71+4.63)/4 =5.495.

These Average Effects have been shown in Table 4.

**Table 4. The Average Effects of various factors affecting surface roughness in Wire EDM process.**

| **Factor** | **Factor description** | ***Level 1, L1*** | ***Level 2, L2*** | ***Level 3, L3*** | ***Level 4, L4*** |
|---|---|---|---|---|---|
| A | Work piece composition | 5.4 | 5.7 | - | - |
| B | Nozzle workpiece distance | 5.6 | 5.441 | - | - |
| C | Wire feed rate | 5.6 | 5.4 | - | - |
| D | Machining Current | 6.2 | 5.3 | 5.6 | 5.018 |
| E | Gap voltage | 4.8 | 4.9 | 5.4 | 7.015 |
| F | Wire tension | 5.4 | 5.3 | 5.8 | 5.603 |
| G | Dielectric flow rate | 5.5 | 4.8 | 6.3 | 5.495 |

### *5.2. Calculations for sum of squares of factors and their percentage contribution*

Based on the Table 4 given above, we next calculated the sum of square of each factor.

Table 5.1. Calculating Means of levels

| **Factor** | **Factor description** | ***Level 1, L1*** | ***Level 2, L2*** | ***Level 3, L3*** | ***Level 4, L4*** | ***m Mean of Levels (x*** |
|---|---|---|---|---|---|---|
| A | Work piece composition | 5.42 | 5.71 | - | - | 5.56 |
| B | Nozzle workpiece distance | 5.69 | 5.44 | - | - | 5.56 |
| C | Wire feed rate | 5.66 | 5.47 | - | - | 5.56 |
| D | Machining Current | 6.28 | 5.3 | 5.65 | 5.02 | 5.56 |
| E | Gap voltage | 4.8 | 5 | 5.44 | 7.02 | 5.56 |
| F | Wire tension | 5.49 | 5.33 | 5.84 | 5.6 | 5.56 |
| G | Dielectric flow rate | 5.5 | 4.89 | 6.37 | 5.5 | 5.56 |

The Means of Levels of various factors were then used by us to find out the Percentage Contribution of each factor, as shown in Table 5.2 and Table 5.3.

**Table 5.2. Calculating Σ for Percentage Contribution**

| **Factor** | **Factor description** | **$(L1-x_m)^2$** | **$(L2-x_m)^2$** | **$(L3-x_m)^2$** | **$(L4-x_m)^2$** | **Σ** |
|---|---|---|---|---|---|---|
| A | Work piece composition | 0.022201 | 0.022201 | - | - | 0.0444402 |
| B | Nozzle workpiece distance | 0.015006 | 0.015006 | - | - | 0.0300113 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| C | Wire feed rate | 0.009025 | 0.009025 | - | - | 0.018050 |
| D | Machining Current | 0.515524 | 0.068121 | 0.007921 | 0.298116 | 0.889682 |
| E | Gap voltage | 0.579121 | 0.320356 | 0.015376 | 2.105401 | 3.020254 |
| | Wire tension | 0.006241 | 0.057121 | 0.077841 | 0.001521 | 0.142724 |
| G | Dielectric flow rate | 0.003721 | 0.454276 | 0.646416 | 0.004761 | 1.109174 |

**Table 5.3. Calculations for Percentage contribution**

| Factor | Σ | D.F. | Sum of squares | Contribution | Contribution (%) |
|---|---|---|---|---|---|
| A | 0.044402 | 1 | 0.044402 | 0.0245 | 2.45 |
| B | 0.030013 | 1 | 0.030013 | 0.0166 | 1.66 |
| C | 0.018050 | 1 | 0.018050 | 0.0100 | 1 |
| D | 0.889682 | 3 | 0.296561 | 0.1636 | 16.36 |
| E | 3.020254 | 3 | 1.006751 | 0.5553 | 55.53 |
| F | 0.142724 | 3 | 0.047575 | 0.0262 | 2.62 |
| G | 1.109174 | 3 | 0.369725 | 0.2039 | 20.39 |

The percentage contribution of all these factors have been shown in Figure 11. It is clearly seen that Gap Voltage has maximum effect on the surface roughness values, followed by Dielectric flow rate and machining current, respectively.

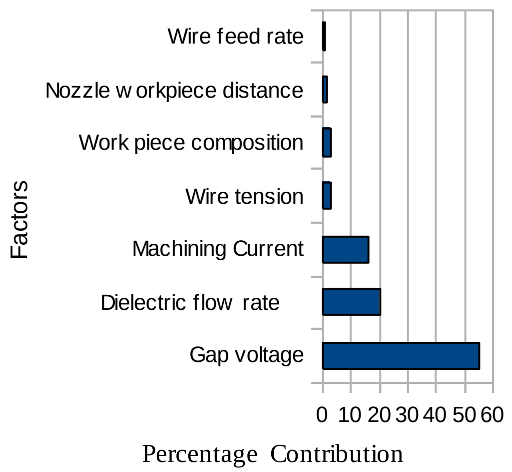


Fig. 11. Comparison of percentage contribution of various factors in wire EDM machining of Al SiC 6061 MMC.

***5.3. Calculations for Main Effects of surface roughness***

In order to calculate the Main Effects of various parameters affecting surface roughness, the Average Effects of each factor are plotted on a graph, one by one. This is done by placing the Average Effects along the x-axis and the factor levels along the y-axis of all the factors. The plots obtained have been shown below from Figure 12 to 18.

*5.3.1. Main Effects of the factor of workpiece composition*

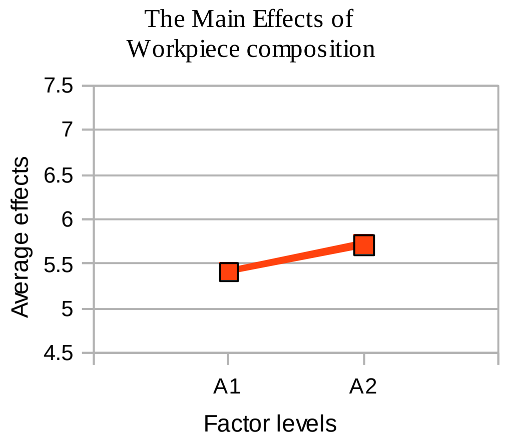


**Fig. 12. A graphical plot showing the Main Effects of factor A (the percentage of SiC in Al SiC MMC specimens). X axis has 5% SiC composition as A1 and 10% SiC composition as A2 whereas Y axis shows Average Effects in units of $R_q$.**

The surface roughness value needs to be minimized. Hence, from Figure 12, we see that the factor level that shall result in minimum value of surface roughness corresponds to A1.

*5.3.2. Main Effects of the factor of Nozzle workpiece distance*

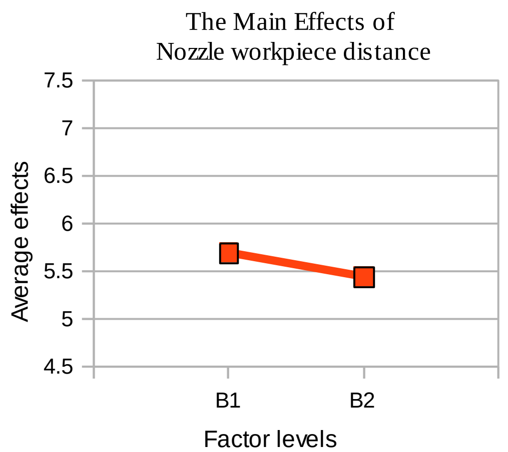


**Fig. 13. A graphical plot showing the Main Effects of factor B (Nozzle workpiece distance). Y axis has Average Effects in units of $R_q$. X axis has 40 mm as level B1 and 50 mm as level B2 in units of mm.**

The value of surface roughness needs to be minimized. Hence, from Figure 13, we see that the factor level that shall result in minimum value of surface roughness corresponds to B2.

*5.3.3. Main Effects of the factor of wire feed rate*

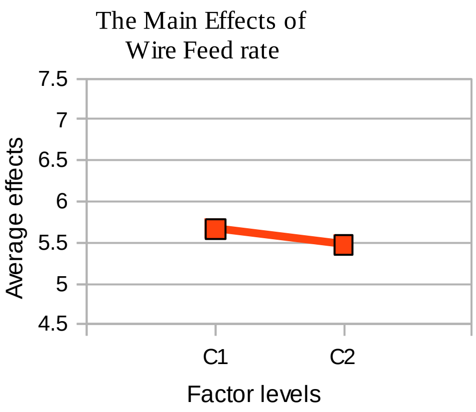


**Fig. 14. A graphical plot showing the Main Effects of factor C (Wire feed rate). Y axis has Average Effects in units of $R_q$. X axis has 3 m/min as level C1 and 5 m/min as level C2.**

The value of surface roughness needs to be minimized. Hence, from Figure 14, we see that the factor level which shall result in minimum value of surface roughness corresponds to C2.

*5.3.4. Main Effects of the factor of Machining current*

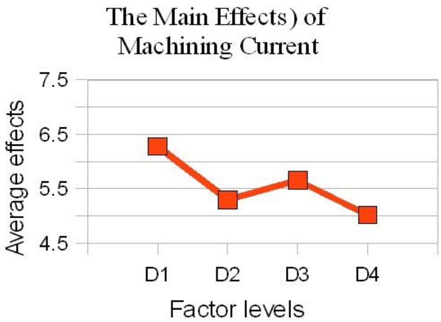


**Fig. 15. A graphical plot showing the Main Effects of factor D (machining current). Y axis has Average Effects in units of $R_q$. X axis has machining current as a factor at levels D1, D2, D3, and D4 in units of ampere.**

The value of surface roughness needs to be minimized. Hence, from Figure 15, we see that the factor level which shall result in minimum value of surface roughness corresponds to D4.

*5.3.5. Main Effects of the factor of gap voltage*

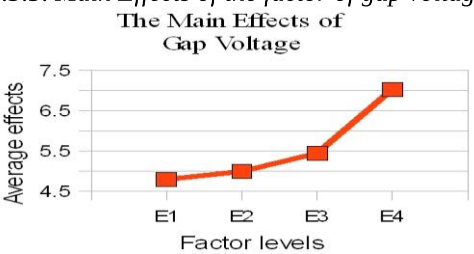


**Fig. 16. A graphical plot showing the Main Effects of factor E (gap voltage). Y axis has Average Effects in units of $R_q$. X axis has gap voltage as a factor at levels E1, E2, E3, and E4 in units of volts.**

The value of surface roughness needs to be minimized. Hence, from Figure 16, we see that the factor level which shall result in minimum value of surface roughness corresponds to E1.

*5.3.6. Main Effects of the factor of wire tension*

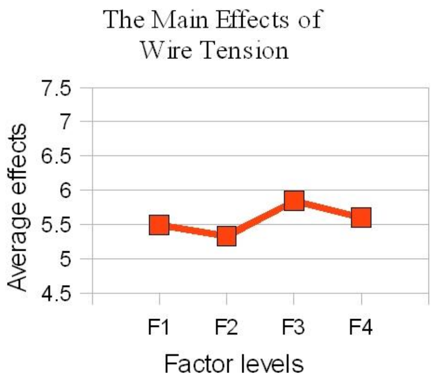


**Fig. 17. A graphical plot showing the Main Effects of factor F (wire tension ). Y axis has Average Effects in units of $R_q$ and X axis has (wire) tension as a factor at levels F1, F2, F3, and F4 in units of grams.**

The value of surface roughness needs to be minimized. Hence, from Figure 17, we see that the factor level which shall result in minimum value of surface roughness corresponds to F2.

*5.3.7. Main Effects of the factor of dielectric flow rate*

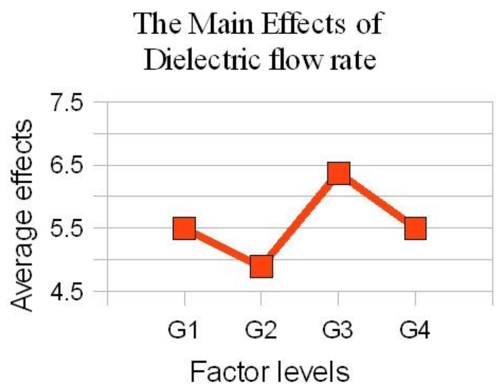


**Fig. 18. A graphical plot showing the Main Effects of factor G (dielectric flow rate ). Y axis has Average Effects in units of $R_q$. X axis has dielectric flow rate as a factor at levels G1, G2, G3, and G4 in units of l.p.m.**

The value of surface roughness needs to be minimized. Hence, from Figure 18, we see that the factor level which shall result in minimum value of surface roughness corresponds to G2.

From the graphical plots shown above, we see that the levels of various factors which shall result in a low value of surface roughness corresponds to A1, B2, C2, D4, E1, F2, and $G_{2.}$

The levels of various factors that shall result in minimum value of surface roughness have been shown in tabular form, as in Table 6.

**Table 6. Levels of factors for minimum value of surface roughness.**

| Factor | Factor Description | Levels for minimum surface roughness |
|---|---|---|
| A | Work piece composition | SiC 5% |
| B | Nozzle workpiece distance | 50 mm |
| C | Wire feed rate | 5 m/min |
| D | Machining Current | 1.25 A |
| E | Gap voltage | 60 V |
| F | Wire tension | 1000 g |
| G | Dielectric flow rate | 1.5 l.p.m. |

Selection of optimal parameters play important role for achieving better cutting speed, better removal rate, and higher surface finish [11]. In order to attain good surface finish, there is need to control the influencing parameters like dielectric medium, material and electrical parameters [12]. It is deemed that the above mentioned levels of the given factors which shall result in minimum value of surface roughness.

### *5.2. Calculations for Projection of optimal performance*

According to the usual notations, here,
Total number of observations, N = 16
Sum total of all observations, T
= 5.5 + 5 + 6.83 + 7.8 + 4.64 + 4.74 + 4.84 + 6.99 + 4.71 + 5.41 + 5.46 + 7.03 + 4.36 + 4.84 + 4.63 + 6.24
= 89.02.
Using the relation for optimal performance,
$Y_{optimal} = T/N + (A_1 - T/N) + (B_2 - T/N) + (C_2 - T/N) + (D_4 - T/N) + (E_1 - T/N) + (F_2 - T/N) + (G_2 - T/N)$
= 5.56 + (5.42 -5.56) + (5.44 -5.56) + (5.47 - 5.56) + (5.02-5.56) + (4.8-5.56) + (5.33-5.56) + (4.89-5.56)
= 5.56+ (- 0.14) + (-0.12) + (- 0.09)+ (-0.54) + (-0.76) + (-0.23) + (-0.67)
**= 3.01** μm**.**

## VI. CONFIRMATION TEST

In order to confirm the accuracy of predicted values, a total of three tests were performed and hence, three specimen pieces were obtained by us on wire EDM machine at the experimental factors which have been described in Table 6. We measured the surface roughness values on all these three specimen pieces at five random points on their surfaces and then took the average values. The calculations have been shown in Table 7.

| ***Specimen piece no.*** | **Measured values (*μm*)** | | | | | **Mean values (*μm*)** | **Average value (*μm*)** |
|---|---|---|---|---|---|---|---|
| | ***1st*** | ***2nd*** | ***3rd*** | ***4th*** | ***5th*** | | |
| 1 | 4.16 | 3.51 | 3.18 | 3.73 | 3.42 | 3.6 | 3.52 |
| 2 | 3.21 | 2.8 | 3.35 | 3.83 | 3.88 | 3.41 | |
| 3 | 3.4 | 3.12 | 3.61 | 3.51 | 3.54 | 3.54 | |

The value of average surface roughness obtained during confirmation tests was compared by us with the values earlier obtained using the relation for optimal performance. We found that the actual values were 116.94% of the calculated values which are quite satisfactory. Their comparison has been shown graphically in Figure 19.

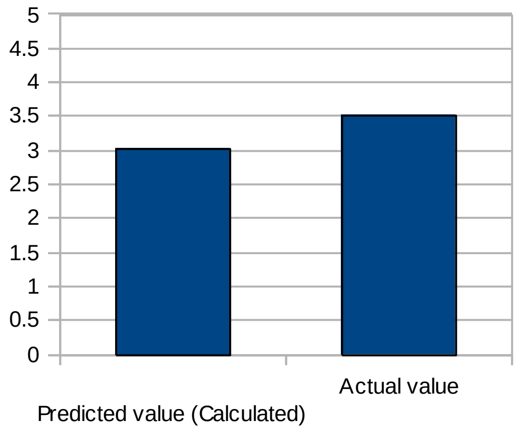


**Fig. 19. Comparison of predicted values which had been obtained theoretically by mathematical relations with those obtained during the confirmation tests.**

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