Optimization of micro hardness of Al-SiC 6061 MMC machined by Wire EDM with Taguchi method

Rohit Sharma, Vivek Aggarwal, H. S. Payal

Abstract: The usage of Al-SiC metal matrix composites is constantly increasing since the last many years due to their many unique properties such as light weight, high strength, high specific modulus, high fatigue strength, low density, and high hardness. However, because of their high hardness, their machining, that too within close tolerance limits, is often a big challenge. Wire EDM (Electric Discharge Machining) however offers a good method to machine these deemed difficult to machine alloys. This research work focuses on the wire EDM machining of Al-SiC 6061 metal matrix composite which is one of the most widely used metal matrix composites in the world today. Here, Taguchi approach has been applied to study the work-piece composition and machining parameters during the wire EDM machining and to maximize the micro hardness of the surface obtained after the machining process. Different compositions of the Al-SiC MMC in terms of reinforcement percentages, along with six other operating parameters have been studied. L-16 Orthogonal Array (pronounced as ell-sixteen Orthogonal Array) has been used in the Taguchi approach for this purpose. Contributions of various factors to surface micro hardness have been determined, amongst which, SiC percentage in the Al-SiC MMC had the greatest contribution. The conclusions and future scope of this study have also been discussed.

Keywords: Al SiC, 6061, composite, micro hardness, MMCs, Orthogonal Arrays, Taguchi, Wire Electric Discharge Machining.

I. INTRODUCTION

This work analyzes the various factors (also known as parameters) involved in the machining by wire-cut EDM machine. Conventional machine tools such as routers, saws, and lathes are often not suitable for machining composites and high strength alloys [1].

Wire EDM is hence one of the non-conventional methods used for machining such materials. It is one of the widely accepted advanced manufacturing processes used to machine complicated materials [2]. Elektra Supercut 734 was the wire EDM machine used by us for this work which uses a brass wire as cutting wire and deionized water as a dielectric. The dielectric is continuously kept in circulation through the machine and filtration unit in a closed circuit. Six factors of the machining process have been involved in this study, namely, the upper nozzle height, the wire feed rate, the (machining) current, the gap voltage, the (wire) tension, and the upper nozzle flow rate.

Along with these six factors, the percentage of SiC particles in Al-SiC 6061 metal matrix composite has also been studied at two levels as specimen composition. Levels are defined as the setting of various factors in a factorial experiment. The Taguchi experimental design has been used for this purpose. It provides an efficient and systematic approach for determining the optimum machining parameters in the manufacturing process [3].

The Al-SiC 6061 which has been used in this work is a Metal matrix composite. Metal matrix composites usually consist of a low-density metal such as aluminum or magnesium, reinforced with particulate or fibers of a ceramic material such as silicon carbide or graphite [4]. As a matter of fact, the most popular type of MMC is aluminum alloy reinforced with ceramic particles [5]. The two variations which have been studied in this work are that of 5% SiC and of 10% SiC reinforcements, respectively. Al-SiC 6061 MMC has the aluminum alloy of Al-6061 (called its matrix phase) with uniformly distributed SiC particles of 220 mesh size (called its reinforcement phase). An MMC having aluminum as its matrix phase is also sometimes called Aluminum Matrix Composite (AMC). These specimens had been prepared by Stir Casting (SC) process. Of various AMC manufacturing techniques, stir casting has the advantage of being the simplest, most flexible and cheapest process of all [6].

An Orthogonal Array (OA) is a mathematical invention recorded by Jacques Hadamard, a French mathematician in as early as 1897 [7]. Orthogonal Array of I-16 type had been found to be most appropriate for the study, hence had been employed. A factor is another name of a parameter in experiments. The most favorable levels of each of the seven factors (six factors are the machining parameters of the machine, and the seventh factor is that of the specimen composition; hence total seven factors) have been found out. Percentage contribution of each of these factors has also been worked out which describe that how dominantly each of these factors contributes to the final hardness of machined surfaces on this machine.

II. MATERIALS AND METHODS

Composition analysis of the Al-6061 alloy was done by atomic emission spectrometry as per the ASTM E1251-2011 test method. Its results were tallied with statistically available data regarding Al-6061 alloy and the alloy was deemed authentic and hence acceptable for further research. The test results have been shown in Table 1 below,
MMC was prepared out of this Al-6061 by stir casting process. Stir casting method involves the incorporation of reinforcements into liquid matrix melt through continuously stirring resulting into vortex mixing that enables the proper distribution of the reinforcements. The mixture of metal and reinforcement, called slurry, is allowed to solidify inside the pre-fabricated mold cavity [8]. SiC powder of 220 mesh size had been taken as reinforcement phase and preheated to a temperature of 3500°C. SiC is the best strengthening reinforcement since it is having a higher value of Vickers (hardness) [9]. This temperature was maintained for about half an hour so as to remove moisture and volatile matter. The carefully weighed Al-SiC alloy was heated in a vertical muffle furnace to about 850°C, and the preheated SiC particles were then added to them. 1% by weight magnesium ribbon strip was also put in the crucible so as to increase the wettability issues or lack of interaction in-between, the final composite will have poor mechanical properties [10]. A stirrer of graphite was left to rotate in the molten slurry for some time. After removal of slag, the metal poured into two specially prepared cylinder molds, one with 5% SiC composition and another of the 10% SiC composition, respectively.

After preparation of the 5% and 10% SiC specimens to be used for the final experimental work, SEM was carried out on the 10% specimen because the percentage of particles was more in it. Scanning Electron Microscope - JSM 6100 of JEOL make was used for this purpose. The result has been shown in Figure 1.

![SEM photograph showing SiC particles as the reinforcement phase which is embedded in the Al 6061 as the matrix phase.](image1)

Fig. 1. The model showing the red colored surface being machined on a specimen. This is the surface which has been resulted from the first experimental setting and its hardness values are to be used in further analysis. Twenty four of these machining cuts had been done on the 5% SiC MMC specimen and twenty four had been done on the 10% SiC MMC specimen as per the guidelines of 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 model is shown in Figure 2, and the actual cut out pieces have been shown in Figure 3.

![The cut out semi-circular disc-shaped specimens whose surfaces had to be analyzed for their micro hardness values and considered in the Taguchi method.](image3)

Table 1. Spectrometry test results of Aluminium 6061.

| Element | Cu | Mg | Si | Fe | Ni | Mn |
|---------|----|----|----|----|----|----|
| Percentage | 0.20 | 0.93 | 0.78 | 0.30 | 0.00 | 0.083 |
| Percentage | 0.30 | 30 | 40 | 32 | 6 |

![Table 1. Spectrometry test results of Aluminium 6061.](image2)

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The micro hardness values of these tests had been performed on the Rockwell hardness testing machine with diamond tip indenter, as shown in Figure 4 and Figure 5.
Fig. 4. Rockwell micro hardness testing machine (details). The yellow rectangle indicates the turret on which the specimen was needed to be placed, the green rectangle shows the hand wheel for application of minor load on the specimen, and the red rectangle shows the lever for the release of major load on the surface of specimen by the indenter.

In order to conduct the micro hardness tests of the pieces obtained from the specimens after wire EDM machining, according to tables, the diamond tip indenter for a load of 60 kg was selected. This indenter was mounted on the turret upside down over the test table by us. After a specific semi-circular disc-shaped specimen was placed with its test surface towards the top on the test table whose position has been shown by a yellow circle, the hand wheel beneath it was rotated by us so as to raise it to touch the indenter. The indenter has been explained briefly in Figure 5.

Fig. 5. The increment in depth is a measure of hardness of specimen in a diamond rockwell tester.

III. RESULTS AND DISCUSSION

3.1. Design of experiments

Five readings had been taken on the surface of each specimen, and their averages had been considered in the study. Table 2 shows these 16 values which we next used in the orthogonal array.

Table 2. Average micro hardness obtained during machining at each setting of Orthogonal Array (numbered 1 to 16).

| S. No. | Specimen 1 to 16 (HRA) | Specimen 17 to 32 (HRA) | Specimen 33 to 48 (HRA) | Average (1 to 16) (HRA) |
|-------|------------------------|-------------------------|-------------------------|-------------------------|
| 1     | 75.2                   | 72.4                    | 83.6                    | 77.1                    |

As per the standard method of Taguchi analysis of orthogonal arrays, these 16 values had been placed on the right side of the L16 orthogonal array (in orange colored blocks). Rows and columns have been colored for better comprehension, as shown in Table 3 below.
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3.2. Mathematical analysis

3.2.1. Calculations for Average Effects of micro hardness

Based on Table 3 given above, next, the Average Effects of micro hardness were calculated. The calculations have been shown below.

Average Effects of A at levels 1 and 2,

\[ A_1 = \frac{(77.1 + 76.5 + 79.5 + 82.5 + 81.5 + 82.6 + 84.5 + 80.7)}{8} = 80.625 \]

Average Effects of B at levels 1 and 2,

\[ B_1 = \frac{(77.1 + 86.7 + 88.3 + 82.6 + 88.4 + 88.6 + 84.5)}{8} = 84.850 \]

Average Effects of C at levels 1 and 2,

\[ C_1 = \frac{(77.1 + 88.1 + 88.3 + 87.9 + 81.5 + 87.3 + 88.7 + 80.7)}{8} = 83.875 \]

Average Effects of D at levels 1, 2, 3, and 4,

\[ D_1 = \frac{(77.1 + 76.5 + 86.7 + 88.1)}{4} = 82.100 \]

\[ D_2 = \frac{(88.3 + 88.3 + 79.5 + 82.6)}{4} = 84.675 \]

D_3 = (81.5 + 82.6 + 87.3 + 88.4) / 4 = 84.950,

D_4 = (88.6 + 88.7 + 84.5 + 80.7) / 4 = 85.625.

Average Effects of E at levels 1, 2, 3, and 4,

\[ E_1 = \frac{(77.1 + 88.3 + 81.5 + 88.6)}{4} = 83.875 \]

\[ E_2 = \frac{(76.5 + 88.3 + 82.6 + 88.7)}{4} = 84.025 \]

\[ E_3 = \frac{(86.7 + 79.5 + 87.3 + 84.5)}{4} = 84.500 \]

\[ E_4 = \frac{(81.1 + 82.6 + 88.4 + 80.7)}{4} = 84.950 \]

Average Effects of F at levels 1, 2, 3, and 4,

\[ F_1 = \frac{(77.1 + 88.3 + 87.3 + 80.7)}{4} = 85.625 \]

\[ F_2 = \frac{(76.5 + 88.3 + 88.4 + 84.5)}{4} = 84.425 \]

\[ F_3 = \frac{(86.7 + 82.6 + 81.5 + 88.7)}{4} = 84.875 \]

\[ F_4 = \frac{(81.1 + 79.5 + 82.6 + 88.6)}{4} = 84.700 \]

Average Effects of G at levels 1, 2, 3, and 4,

\[ G_1 = \frac{(77.1 + 88.3 + 88.4 + 88.7)}{4} = 85.625 \]

\[ G_2 = \frac{(76.5 + 88.3 + 87.3 + 88.6)}{4} = 85.175 \]

\[ G_3 = \frac{(86.7 + 82.6 + 82.6 + 80.7)}{4} = 83.150 \]

\[ G_4 = \frac{(81.1 + 79.5 + 81.5 + 84.5)}{4} = 83.400 \]

These Average Effects can be summarized, as shown in Table 4.

| Factor | Factor name             | Level | Level | Level | Level |
|--------|-------------------------|-------|-------|-------|-------|
| A      | Work-piece              | 80.62 | 88.05 | -     | -     |
| B      | Upper nozzle height     | 84.85 | 83.82 | -     | -     |
| C      | Wire feed rate          | 84.90 | 84.33 | -     | -     |
| D      | Current                 | 82.10 | 84.67 | 84.95 | 85.62 |
| E      | Gap voltage             | 83.87 | 84.02 | 84.50 | 84.95 |
| F      | Tension                 | 83.35 | 84.42 | 84.87 | 84.70 |
| G      | Upper nozzle flow rate  | 85.62 | 85.17 | 83.15 | 83.40 |

3.2.2. Calculations for sum of squares of factors and their percentage contribution

Based on Table 4 given above, next, the sum of squares of each factor is calculated. Furthermore, the sum of squares have been used to calculate the percent contribution of various factors for micro hardness. This has been shown in Table 5 to Table 8 below.

Table 5. Means of Levels.

| Factor | Level 1, L1 | Level 2, L2 | Level 3, L3 | Level 4, L4 | Mean of Levels (x̄) |
|--------|-------------|-------------|-------------|-------------|---------------------|
| A      | 80.62       | -           | -           | -           | 84.34              |
| B      | 84.85       | 83.82       | -           | -           | 84.338             |
| C      | 84.90       | 83.77       | -           | -           | 84.338             |
Table 6. Calculations of Percent Contribution for micro hardness.

| Factor | \( L1 - x_m \) | \( L2 - x_m \) | \( L3 - x_m \) | \( L4 - x_m \) |
|--------|----------------|----------------|----------------|----------------|
| A      | -3.713         | 3.712          | -              | -              |
| B      | 0.512          | -0.513         | -              | -              |
| C      | 0.562          | -0.563         | -              | -              |
| D      | -2.238         | 0.337          | 0.612          | 1.287          |
| E      | -0.463         | -0.313         | 0.162          | 0.612          |
| F      | -0.988         | 0.087          | 0.537          | 0.362          |
| G      | 1.287          | 0.837          | -1.188         | -0.938         |

Fig. 7. Graphical representation of the main effects of factor A (both specimens' SiC percentage). Y-axis has Average Effects in units of HRA and X-axis has 5% SiC composition specimen as A1 and 10% SiC composition as A2.

The micro hardness needs to be maximized. Hence, on the visual examination of Figure 7 above, we see that the factor level that shall result in a higher value of micro hardness is A2.
3.3.2. Main effects of factor B

In the context of the upper nozzle height of the wire EDM machine, the plots of the main effects have been shown below.

We plotted the Average Effects, depicted in Table 4 along the y-axis and the levels of factors along the x-axis in Figure 8.

![Graphical representation of the main effects of factor B](image1)

Fig. 8. Graphical representation of the main effects of factor B (upper nozzle height). Y-axis has Average Effects in units of HRA and X-axis has 40 mm as B1 and 50 mm as B2. The micro hardness needs to be maximized. Hence, on the visual examination of Figure 8 above, we see that the factor level that shall result in a higher value of micro hardness is B1.

3.3.3. Main effects of factor C

In the context of the wire feed rate, the plots of the main effects have been shown below.

We plotted the Average Effects, depicted in Table 4 along the y-axis and the levels of factors along the x-axis in Figure 9.

![Graphical representation of the main effects of factor C](image2)

Fig. 9. Graphical representation of the main effects of factor C (wire feed rate). Y-axis has Average Effects in units of HRA and X-axis has wire feed rate as level C1 and level C2 in units of m/min. The micro hardness needs to be maximized. Hence, on the visual examination of Figure 9 above, we see that the factor level that shall result in a higher value of micro hardness is C1.

3.3.4. Main effects of factor D

In the context of the (machining) current used in the Wire EDM machine, the plots of the main effects have been shown below.

We plotted the Average Effects, depicted in Table 4 along the y-axis and the levels of factors along the x-axis in Figure 10.

![Graphical representation of the main effects of factor D](image3)

Fig. 10. Graphical representation of the main effects of factor D (machining current). Y-axis has Average Effects in units of HRA and X-axis has machining current as a factor at levels D1, D2, D3, and D4 in units of amperes.

The micro hardness needs to be maximized. Hence, on the visual examination of Figure 10 above, we see that the factor level that shall result in a higher value of micro hardness is D3.

3.3.5. Main effects of factor E

In the context of the gap voltage between the electrode wire of the Wire EDM machine and the workpiece to be machined, the plots of the main effects have been shown below.

We plotted the Average Effects, depicted in Table 4 along the y-axis and the levels of factors along the x-axis in Figure 11.

![Graphical representation of the main effects of factor E](image4)

Fig. 11. Graphical representation of the main effects of factor E (gap voltage). Y-axis has Average Effects in units of HRA and X-axis has gap voltage as a factor at levels E1, E2, E3, and E4 in units of volts.

The micro hardness needs to be maximized. Hence, on the visual examination of Figure 11 above, we see that the factor level that shall result in a higher value of micro hardness is E4.

3.3.6. Main effects of factor F

In the context of the wire tension in the (machining) wire of Wire EDM machine, the plots of the main effects have been shown below.

We plotted the Average Effects, depicted in Table 4 along the y-axis and the levels of factors along the x-axis in Figure 12.
It is deemed that the above-mentioned levels of the given factors were to result in a higher value of micro hardness.

3.4. Projection of optimal performance (micro hardness)

According to the usual notations, here, Total number of observations, \( N = 16 \)

Sum total of all observations, \( T = 77.1 + 76.5 + 86.7 + 88.1 + 88.3 + 88.3 + 79.5 + 82.6 + 81.5 + 82.6 + 87.3 + 88.4 + 88.6 + 88.7 + 84.5 + 80.7 \)

\( = 1349.4 \).

Optimal performance, \( Y_{optimal} = \frac{T}{N} + (A_2 - \frac{T}{N}) + (B_1 - \frac{T}{N}) + (C_1 - \frac{T}{N}) + (D_1 - \frac{T}{N}) + (E_1 - \frac{T}{N}) + (F_1 - \frac{T}{N}) + (G_1 - \frac{T}{N}) \)

\( = 84.338 + (88.050 - 84.338) + (84.850 - 84.338) + (84.900 - 84.338) + (84.950 - 84.338) + (84.975 - 84.338) + (84.875 - 84.338) + (85.625 - 84.338) \)

\( = 84.338 + (3.712) + (0.512) + (0.562) + (0.612) + (0.612) + (0.537) + (1.287) \)

\( = 92.172 \text{ HRA} \).

IV. CONFIRMATION TESTS

It is recommended that the projected optimal performance should be checked by running confirmatory tests. After the aforesaid calculations were made, confirmatory experiments were carried out by us as per the parameter settings of Table 9.

A total of three tests were performed by us, and hence, we prepared three specimens. All these specimens were prepared by us from the SiC 10 % composition casting which corresponds to A2. In order to prepare these specimens, the SiC 10 % composition casting was mounted by us on the Wire EDM machine. We set the various parameters according to the Table 9, after which, the machining cuts were made on the casting. This resulted in three specimens which had been cut on the parameter settings recommended for obtaining maximum micro hardness value. Similar to the earlier cut specimens during the test, the micro hardness values were measured by us on all these three specimens at five random points on their surfaces on the same micro hardness testing machine, and the average of these five points was taken by us. Then we took the average micro hardness values of these three specimens. The readings have been shown in Table 10 below.

Table 10. Confirmation tests for micro hardness.

| Specimen number | Micro hardness (HRA) | Average (HRA) |
|-----------------|----------------------|---------------|
| Specimen number | 1st din | 2nd din | 3rd din | 4th din | 5th din | MH |
| C1              | 90    | 89    | 91    | 90    | 90    | 90.000 | 91.13 |

Fig. 12. Graphical representation of the main effects of factor F (wire tension). Y-axis has Average Effects in units of HRA and X-axis has (wire) tension as a factor at levels F1, F2, F3, and F4 in units of grams.

The micro hardness needs to be maximized. Hence, on the visual examination of Figure 12 above, we see that the factor level that shall result in a higher value of micro hardness is F3.

3.3.7. Main effects of factor G

In the context of the upper nozzle flow rate, the plots of the main effects have been shown below.

We plotted the Average Effects, depicted in Table 4 along the y-axis and the levels of factors along the x-axis in Figure 13.

The micro hardness needs to be maximized. Hence, on the visual examination of Figure 13 above, we see that the factor level that shall result in a higher value of micro hardness is G1.

From the visual examination of figures above, we see that the levels of various factors that shall result in a high value of micro hardness correspond to A2, B1, C1, D1, E1, F1, and G1. The levels of various factors that shall result in a high value of micro hardness can be shown in tabular form, as in Table 9.

Table 9. Levels of factors for maximization of micro hardness.

| Factor Name | Factor Description | Factor Levels | Factor Values |
|-------------|--------------------|---------------|---------------|
| A           | Work-piece         | A2            | SIC 10 %      |
| B           | Upper nozzle height| B1            | 40 mm         |
| C           | Wire feed rate     | C1            | 3 m/min       |
| D           | Current            | D1            | 1 A           |
| E           | Gap voltage        | E1            | 72 V          |
| F           | Tension            | F1            | 1100 g        |
| G           | Upper nozzle flow  | G1            | 1 l.p.m.      |
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These results have been shown graphically in Figure 14 on being compared with their accuracy of predicted values.

Fig. 14. Comparison of predicted and actual values of micro hardness obtained after the confirmation tests.

The value of micro hardness which had been calculated by projection of optimal performance are 101.143% of the actual values which are quite satisfactory.

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