# Surface Integrity analysis in Wire-Cut Electric Discharge Machining of Al 6063/Al2O3 Metal Matrix Composite through Response Surface Methodology

K.Hemalatha[1], V.S.K.Venkatachalapathy[2] N.Alagumurthy[3]

**Abstract**— The development of new, superior engineering materials and the need for precise and low-volume production have made the wire electrical discharge machining (EDM) an important manufacturing process to meet such demands. This research investigates the effect of pulse on-time, pulse off-time and servo feed, three important WEDM process in obtaining good surface finish, optimized material removal rate and kerf on newly formulated Aluminum 6063/$Al_2O_3$ composite. Stir casting process is adopted for casting the composite plates with varying mass percentage of alumina (3%, 6%, 9%). The distribution of alumina and aluminium is examined by microstructure analysis, and the material is tested for its mechanical properties such as tensile strength and hardness. The effects of the parameters on the responses were evaluated by response surface methodology, which is based on optimization results. On the basis of optimization results it has been found that a pulse duration (Ton) of 3µs & pulse off time (Toff) 17µs and servo feed 7mm/min, which are the best combination of this analysis.

**Index Terms**— Surface integrity, *Aluminum-Alumina composite, Stir casting process, wire electrical discharge machining, pulse on-time, pulse off-time, servo speed, weight percentage of alumina, response surface methodology, kerf, surface roughness*

## 1 INTRODUCTION

The development of new, superior engineered materials and the necessitate for light weight, high stiffness, good wear resistance and low thermal expansion coefficient lead to the development of Al/ $Al_2O_3$ Metal Matrix Composite. Its main function is to transmit and distribute the load to the reinforcement or fibers. This transfer of load depends on the bonding which depends on the type of matrix and reinforcement and the fabrication technique.[1,2] . Nowadays researchers all over the world are focusing mainly on Aluminium because of its unique combination of good corrosion resistance, low density and excellent mechanical properties. The unique thermal properties of Aluminium composites such as metallic conductivity with coefficient of expansion that can be tailored down to zero, add to their prospects in aerospace and avionics. [3, 4].

Also, the practice of hard and difficult to machine materials, due to its brilliant technological properties, is extensively used in various sectors in modern manufacturing industries. Owing to, its excellent properties and behavior in these applications even more challenging, its transformation and processing they present problems which limit the accuracy and rising production costs. Consequently, the machining of such material in an efficient manner is a challenge.

- *K.Hemalatha currently pursuing Ph.D degree program in Mechanical engineering in Pondicherry Engineering College, India, E-mail: hemalatharohit@gmail.com*
- *Dr.V.S.K.Vemkatachalapathy, Professor, Department of Mechanical Engineering, Sri Manakula Vinayagar Engineering College, Puducherry, India,Email:vskvenkatachalapathy@yahoo.com*
- *Dr.N.Alagumurthi, Professor, Department of Mechanical Engineering, Pondicherry Engineering College, Puducherry, India*

Wire-Cut Electro Discharge Machining (EDM) is a brilliant solution to this problem, It is generally used to machine difficult-to-machine materials, high strength, temperature resistant alloys and manufacturing of tools and dies for machining cavities and counter shaping and cutting.[5]

## 2 MATERIALS AND METHODS

The material used in the present investigation consists of Aluminium alloy (Al6063) as the base matrix alloy. Its Chemical composition (%) is Mg = 0.45-0.9, Si=0.2-0.6, Fe=0.35max, Cu=0.1max, Mn=0.1max, Zn=0.1max, Ti=0.1max, Cr=0.1max, Al=balance. It posses high heat dissipation capacity and is suitable for high strength and high temperature applications. The aluminium matrix was reinforced with $Al_2O_3$ of 46 microns in varying percentage of 3%, 6% and 9%.

Typical Stir casting Process includes:

Step1: Aluminium alloy is melted at 800$^0$C in muffle furnace for two hours

Step2:Alumina is melted at 100$^0$ C in another muffle furnace for same time period

Step3:Melted Aluminium & Alumina are mixed in the graphite crucible and 5gm of coverall, nucleant & degasser are added in the melt

Step4:After adding all these, the crucible is kept inside the furnace

Step5:The molten metal are stirred at speed of 200rpm for 10minutes

Step6:At the same time, dies are preheated at 300$^0$ C in another muffle furnace for 2 hours

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Step7:Finally the molten metal poured into the preheated die and then the metal is allowed to solidify

## 3 TESTING AND RESULTS

For the safe design and usage of these composite plates, it is essential that their ultimate strength and mechanical properties need to be determined. Hence various tests are conducted using the fabricated plates.

### 3.1 Tensile Test

The important properties which come into play when a component is subjected to tensile loads are strength, Elasticity & Ductility. The graph below explains detail about the above parameters. From the cast MMC the standard tensile specimen were prepared by machining as per dimensions of ASTM E8. To obtain mechanical properties, specimens with overall length 100mm, thickness of 6mm and a gauge length of 25mm were tested in UNITEX-94100 Universal Testing machine.

### 3.2 Micro Hardness

Hardness is often a function of the particle size, porosity, and binder material. Hardness is very important to the success of machining operations. The hardness of the samples was measured using UHL Vickers micro hardness measuring machine by applying a load of 0.5Kg and this load was applied

TABLE 1
HARDNESS VALUE

| Sample | H.V @ 0.5 Kg Load | | | | |
|---|---|---|---|---|---|
| | Location | | | | Avg |
| **Al6063+3% $Al_2O_3$** | 55.8 | 52.1 | 53.4 | 53.8 | **53.775** |
| **Al6063+6% $Al_2O_3$** | 55.4 | 55.1 | 55.5 | 54.9 | **55.225** |
| **Al6063+9% $Al_2O_3$** | 63.8 | 62.8 | 61.4 | 62.7 | **62.675** |

for 20 seconds. In order to eliminate the possibility of error a minimum of four hardness readings were taken for each sample.

### 3.3 Microstructure Analysis

Microstructure is defined as the structure of a prepared surface or thin foil of material as revealed by a microscope above 25× magnification. The microstructure of a material (which can be broadly classified into metallic, polymeric, ceramic and composite) can strongly influence physical properties such as strength, toughness, ductility, hardness, corrosion resistance, high/low temperature behavior, wear resistance, and so on, which in turn govern the application of these materials in industrial practice.

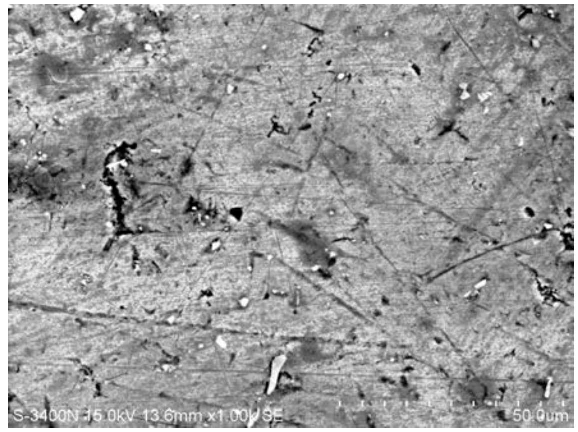


Fig.1. SEM Image of Al6063+9% $Al_2O_3$

Fig.2. SEM Image of Al6063+6% $Al_2O_3$

Fig.3. SEM Image of Al6063+3% $Al_2O_3$

The above SEM images shows creation of grain boundaries the structures show loosely formed grains with Unmodified Vermicular. Silicon segregation in arranged manner of dendrites leading to a "shrinkage prone site". This happen

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due to poor grain refinement as well as poor modification. Thus the casting has all the following defects like shrinkage, gas holes & inclusions. Similar results are reported by [6,7].

## 4 WIRE EDM

Wire EDM (Electrical Discharge Machining) uses electric current and fine wire to cut conductive materials. The cutting typically occurs while the object is submerged in de-ionized water, which helps to cool the process and flush away the cut material. It leaves a smooth surface that often requires no further finishing or polishing. Noted that the cutting wire should not touch the material and that the cutting itself is due to the erosion that occurs when a spark forms between the cutting wire and the raw material.

**Fundamental WEDM Settings:**

The pulse on-time, pulse off-time, servo feed are the basic machine settings.

Other Initial settings include:

Wire diameter: 0.25mm

Wire tension: 0-26 A

Fluid resistivity: 5x$10^4$ Ohm-cm

Fluid Pressure: 12Kg/$Cm^2$

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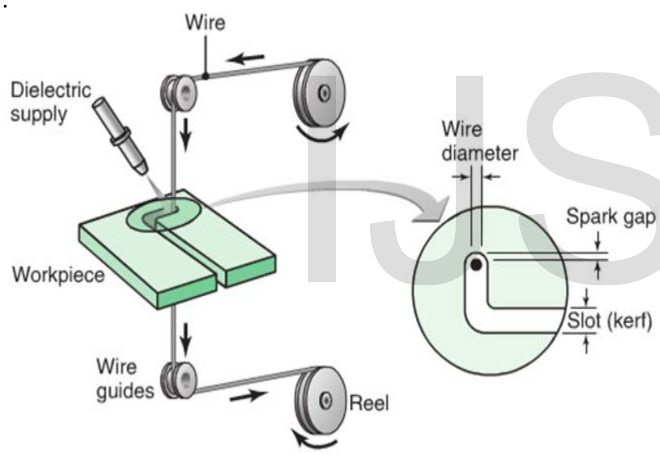


## 5 RESPONSE SURFACE METHODOLOGY

It is multi-response parametric optimization tool which is used to determine the factor levels that will concurrently suit a set of desired Specifications and to resolve the optimum combination of factors that yields a preferred response and describe the response near the optimum.

TABLE 2

THE VALUES AND LEVELS OF THE PROCESS PARAMETERS

| Sl. No. | Process Parameter | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| 1 | Pulse on-time(µs) | 3 | 6 | 9 |
| 2 | Pulse off-time(µs) | 11 | 14 | 17 |
| 3 | Servo feed settings (mm/min) | 5 | 7 | 9 |

TABLE 3

DESIGN MATRIX AND EXPERIMENTAL RESULT FOR 3% ALUMINA

| INPUT PARAMETER | | | | RESPONSE | | |
|---|---|---|---|---|---|---|
| Run | Factor 1 P-ON (µS) | Factor2 P-OFF (µS) | Factor3 Servo Feed (mm/min) | Response 1 SR (µm) | Response2 Kerf (µm) | Response3 MRR ($mm^2$/min) |
| 1 | **6** | **11** | **5** | 2.6 | 287 | **39.9** |
| 2 | 6 | 17 | 9 | 2.2 | 291 | 40 |
| 3 | 6 | 14 | 7 | 2.88 | 289 | 38.956 |
| 4 | 6 | 14 | 7 | 2.7 | 287 | 39 |
| 5 | 6 | 14 | 7 | 2.7 | 290 | 38 |
| 6 | 6 | 17 | 5 | 2.45 | 290 | 38 |
| 7 | 9 | 14 | 5 | 3 | 288 | 35 |
| 8 | 6 | 11 | 9 | 3.5 | 292 | 36 |
| 9 | 3 | 11 | 7 | 2.4 | 284 | 40 |
| 10 | 9 | 11 | 7 | 3.3 | 299 | 37 |
| 11 | 3 | 14 | 9 | 2.22 | 282.5 | 41.89 |
| 12 | 3 | 14 | 5 | 2.11 | 282 | 42 |
| 13 | 9 | 17 | 7 | 3 | 296 | 38 |
| 14 | 3 | 17 | 7 | **2.1** | **280** | **43.8** |
| 15 | 9 | 14 | 9 | 2.9 | 298 | 35 |

TABLE 4

ANNOVA TABLE FOR THE FITTED MODEL: (KERF VALUES)

| SOURCE | DOF | SUM OF SQUARES | MEAN SQUARE | F-RATIO | P-VALUE |
|---|---|---|---|---|---|
| MODEL | **3** | 381.69 | 127.23 | 20.12 | 0.0001 |
| *A-PULSE ON-TIME* | 1 | 344.53 | 344.53 | 54.49 | 0.0001 |
| *B-PULSE OFF-TIME* | 1 | 3.13 | 3.13 | 0.49 | 0.4966 |
| *C-SERVO FEED* | 1 | 34.03 | 34.03 | 5.38 | 0.0406 |

TABLE 6
ANNOVA TABLE FOR THE FITTED MODELS:
(SURFACE ROUGHNESS)

| Source | Degrees of freedom | Sum of Squares | Mean Square | F-ratio | P-Value |
|---|---|---|---|---|---|
| Model | **3** | 2.00 | 0.67 | 12.40 | 0.0007 |
| *A-Pulse on-time* | 1 | 1.42 | 1.42 | 26.42 | 0.0003 |
| *B-Pulse off-time* | 1 | 0.53 | 0.53 | 9.78 | 0.0096 |
| *C-Servo feed* | 1 | 0.054 | 0.054 | 1.01 | 0.3358 |

TABLE 7
R-SQUARED VALUES (SURFACE ROUGHNESS VALUES)

| | | | |
|---|---|---|---|
| Std. Dev. | 0.23 | R-Squared | 0.7718 |
| Mean | 2.67 | Adj R-Squared | 0.7096 |
| C.V. % | 8.68 | Pred R-Squared | 0.5288 |
| PRESS | 1.22 | Adeq Precision | 11.319 |



TABLE 8
ANNOVA TABLE FOR THE FITTED MODELS
(MATERIAL REMOVAL RATE)

| Source | Degrees of freedom | Sum of Squares | Mean Square | F-ratio | P-Value |
|---|---|---|---|---|---|
| Model | **3** | 70.81 | 23.60 | 12.99 | 0.0006 |
| *A-Pulse on-time* | 1 | 64.35 | 64.35 | 35.41 | 0.0001 |
| *B-Pulse off-time* | 1 | 5.95 | 5.95 | 3.27 | 0.0977 |
| *C-Servo feed* | 1 | 0.51 | 0.51 | 0.28 | 0.6086 |

TABLE 9
R-SQUARED VALUES
(MATERIAL REMOVAL RATE)

| | | | |
|---|---|---|---|
| Std. Dev. | 1.35 | R-Squared | 0.7798 |
| Mean | 38.84 | Adj R-Squared | 0.7198 |
| C.V. % | 3.47 | Pred R-Squared | 0.5366 |
| PRESS | 42.08 | Adeq Precision | 10.626 |

TABLE 10
DESIGN MATRIX AND EXPERIMENTAL RESULT FOR 6% ALUMINA

| INPUT PARMETER | | | | RESPONSE | | |
|---|---|---|---|---|---|---|
| **Run** | **Factor 1 P-ON (µS)** | **Factor2 P-OFF (µS)** | **Factor3 Servo Feed (mm/ min)** | **Response1 SR (µm)** | **Response2 Kerf (µm)** | **Response3 MRR $Mm^2$/min** |
| 1 | **6** | 11 | **5** | 2.8 | 284 | 43 |
| 2 | 6 | 17 | 9 | 2.75 | 283.59 | 45 |
| 3 | 6 | 14 | 7 | 3 | 286 | 44 |
| 4 | 6 | 14 | 7 | 2.65 | 283 | 43 |
| 5 | 6 | 14 | 7 | 2.689 | 282.33 | 43 |
| 6 | 6 | 17 | 5 | 2.38 | 280 | 45.5 |
| 7 | 9 | 14 | 5 | 2.9 | 285 | 42 |
| 8 | 6 | 11 | 9 | 3.2 | 286.5 | 42.125 |
| 9 | 3 | 11 | 7 | 2.6 | 281.65 | 45.75 |
| 10 | 9 | 11 | 7 | 3.1 | 287 | 42 |
| 11 | 3 | 14 | 9 | 2.5 | 281 | 46 |
| 12 | 3 | 14 | 5 | 2.3 | 279.2 | 46.25 |
| 13 | 9 | 17 | 7 | 2.9 | 284.1 | 46 |
| 14 | 3 | 17 | 7 | **1.98** | **278** | **47** |
| 15 | 9 | 14 | 9 | 3.1 | 286.95 | 41 |

TABLE 5
R-SQUARED VALUES (KERF VALUES)

| | | | |
|---|---|---|---|
| **Std. Dev.** | 2.51 | R-Squared | 0.8459 |
| **Mean** | 289.03 | Adj R-Squared | 0.8038 |
| **C.V. %** | 0.87 | Pred R-Squared | 0.6811 |
| **PRESS** | 143.90 | Adeq Precision | 13.28 |

TABLE 12
R-SQUARED VALUES (KERF VALUES)

| | | | |
|---|---|---|---|
| **STD. DEV.** | 1.02 | R-SQUARED | 0.8983 |
| MEAN | 283.22 | ADJ R-SQUARED | 0.8705 |
| C.V. % | 0.36 | PRED R-SQUARED | 0.8589 |
| PRESS | 16.03 | ADEQ PRECISION | 17.315 |

TABLE 13
ANNOVA TABLE FOR THE FITTED MODELS:
(SURFACE ROUGHNESS)

| **SOURCE** | **DEGREES OF FREEDOM** | **SUM OF SQUARES** | **MEAN SQUARE** | **F-RATIO** | **P-VALUE** |
|---|---|---|---|---|---|
| MODEL | **3** | 1.39 | 0.46 | 26.52 | 0.0001 |
| *A-PULSE ON-TIME* | 1 | 0.86 | 0.86 | 49.26 | 0.0001 |
| *B-PULSE OFF-TIME* | 1 | 0.36 | 0.36 | 20.49 | 0.0009 |
| *C-SERVO FEED* | 1 | 0.17 | 0.17 | 9.82 | 0.0095 |

TABLE 14
R-SQUARED VALUES (SURFACE ROUGHNESS VALUES)

| | | | |
|---|---|---|---|
| STD. DEV. | 0.13 | R-SQUARED | 0.8785 |
| MEAN | 2.72 | ADJ R-SQUARED | 0.8454 |
| C.V. % | 4.85 | PRED R-SQUARED | 0.7922 |
| PRESS | 0.33 | ADEQ PRECISION | 15.809 |

TABLE 15
ANNOVA TABLE FOR THE FITTED MODELS: (MATERIAL REMOVAL RATE)

| **SOURCE** | **DEGREES OF FREEDOM** | **SUM OF SQUARES** | **MEAN SQUARE** | **F-RATIO** | **P-VALUE** |
|---|---|---|---|---|---|
| MODEL | 3 | 39.47 | 13.16 | 11.82 | 0.0009 |
| *A-PULSE ON-TIME* | 1 | 24.50 | 24.50 | 22.01 | 0.0007 |
| *B-PULSE OFF-TIME* | 1 | 14.11 | 14.11 | 12.68 | 0.0045 |
| *C-SERVO FEED* | 1 | 0.86 | 0.86 | 0.77 | 0.3978 |



TABLE 16
R-SQUARED VALUES (MATERIAL REMOVAL RATE)

| | | | |
|---|---|---|---|
| **STD. DEV.** | 1.05 | **R-SQUARED** | 0.7633 |
| MEAN | 44.11 | ADJ R-SQUARED | 0.6987 |
| C.V. % | 2.39 | PRED R-SQUARED | 0.5405 |
| PRESS | 23.76 | ADEQ PRECISION | 11.301 |

TABLE 11
ANNOVA TABLE FOR THE FITTED MODEL: (KERF VALUES)

| **SOURCE** | **DOF** | **SUM OF SQUARES** | **MEAN SQUARE** | **F-RATIO** | **P-VALUE** |
|---|---|---|---|---|---|
| MODEL | 3 | 102.03 | 34.01 | 32.38 | 0.0001 |
| *A-PULSE ON-TIME* | 1 | 67.28 | 67.28 | 64.06 | 0.0001 |
| *B-PULSE OFF-TIME* | 1 | 22.63 | 22.63 | 21.55 | 0.0007 |
| *C-SERVO FEED* | 1 | 12.12 | 12.12 | 11.54 | 0.0060 |

TABLE 17
DESIGN MATRIX AND EXPERIMENTAL RESULT FOR 9% ALUMINA

| INPUT PARMETER | | | | RESPONSE | | |
|---|---|---|---|---|---|---|
| RUN | FACTOR 1 P-ON (µS) | FACTOR2 P-OFF (µS) | FACTOR3 SERVO FEED (MM/ MIN) | RESPONSE1 SR (µM) | RESPONSE2 KERF (µM) | RESPONSE3 MRR $MM^2/MIN$ |
| 1 | 6 | 11 | 5 | 2.53 | 275 | 49 |
| 2 | 6 | 17 | 9 | 2.178 | 271 | 49.8 |
| 3 | 6 | 14 | 7 | 2.765 | 273 | 47.9 |
| 4 | 6 | 14 | 7 | 2.6 | 272.525 | 48 |
| 5 | 6 | 14 | 7 | 2.612 | 272 | 47 |
| 6 | 6 | 17 | 5 | 2.38 | 270.75 | 46.25 |
| 7 | 9 | 14 | 5 | 2.91 | 275 | 42.75 |
| 8 | 6 | 11 | 9 | 3.3 | 281 | 45 |
| 9 | 3 | 11 | 7 | 2.375 | 273 | 50 |
| 10 | 9 | 11 | 7 | 3.31 | 280 | 44.75 |
| 11 | 3 | 14 | 9 | 2.1 | 272 | 50.25 |
| 12 | 3 | 14 | 5 | 2.0 | 289 | 51 |
| 13 | 9 | 17 | 7 | 2.8 | 270 | 43 |
| 14 | 3 | 17 | 7 | 1.57 | 268 | 52 |
| 15 | 9 | 14 | 9 | 2.75 | 272 | 40 |

TABLE 18
ANNOVA TABLE FOR THE FITTED MODEL: (KERF VALUES)

| Source | DOF | Sum of Squares | Mean Square | F-ratio | P-Value |
|---|---|---|---|---|---|
| Model | **3** | 139.95 | 46.65 | 11.85 | 0.0009 |
| *A-Pulse on-time* | 1 | 28.12 | 28.12 | 7.14 | 0.0217 |
| *B-Pulse off-time* | 1 | 106.95 | 106.95 | 27.17 | 0.0003 |
| *C-Servo feed* | 1 | 4.88 | 4.88 | 1.24 | 0.2891 |

TABLE 19
R-SQUARED VALUES (KERF VALUES)

| | | | |
|---|---|---|---|
| **STD. DEV.** | 1.98 | R-SQUARED | 0.7763 |
| **MEAN** | 272.95 | ADJ R-SQUARED | 0.6993 |
| **C.V. %** | 0.73 | PRED R-SQUARED | 0.4999 |
| **PRESS** | 91.65 | ADEQ PRECISION | 10.797 |

TABLE 21
R-SQUARED VALUES (SURFACE ROUGHNESS VALUES)

| | | | |
|---|---|---|---|
| STD. DEV. | 0.21 | R-SQUARED | 0.8430 |
| MEAN | 2.55 | ADJ R-SQUARED | 0.8002 |
| C.V. % | 8.25 | PRED R-SQUARED | 0.6817 |
| PRESS | 0.98 | ADEQ PRECISION | 14.555 |

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TABLE 22
ANNOVA TABLE FOR THE FITTED MODELS: (MATERIAL REMOVAL RATE)

| Source | Degrees of freedom | Sum of Squares | Mean Square | F-ratio | P-Value |
|---|---|---|---|---|---|
| Model | **3** | 136.68 | 45.56 | 19.69 | 0.0002 |
| *A-Pulse on-time* | 1 | 134.07 | 134.07 | 49.12 | 0.0001 |
| *B-Pulse off-time* | 1 | 0.66 | 0.66 | 0.24 | 0.6323 |
| *C-Servo feed* | 1 | 1.95 | 1.95 | 0.71 | 0.4160 |

TABLE 23
R-SQUARED VALUES (MATERIAL REMOVAL RATE)

| | | | |
|---|---|---|---|
| Std. Dev. | 1.65 | R-Squared | 0.8199 |
| Mean | 47.11 | Adj R-Squared | 0.7708 |
| C.V. % | 3.51 | Pred R-Squared | 0.6227 |
| PRESS | 62.89 | Adeq Precision | 10.754 |

## 6 CONCLUSION

In the research work, a newly formulated composites (Al-$Al_2O_3$) is prepared by the stir casting process. In this stir casting method of casting Al 6063 plate is casted with varying mass of $Al_2O_3$ (3%, 6%, 9%). Also the distribution of Alumina and Aluminium is examined by microstructure analysis, hardness distribution and the material is tested for its mechanical properties such as tensile strength and hardness.

1. The results confirmed that stir casted Al alloy 6063 with $Al_2O_3$ reinforced composite is clearly superior to base alloy Al6063 in the comparison of tensile strength as well as hardness.
2. Tensile strength of Al composite was improved by the addition of the $Al_2O_3$ particles.
3. The Percentage elongation of the composite decreased with increase in $Al_2O_3$ content, which confirms that alumina addition increases brittleness.
4. Increasing of hardness with increasing weight percentage of $Al_2O_3$ particles is mainly due to grain refinement and particle strengthening effects.
5. We found that with respect to decrease in pulse on-time, and weight percentage of alumina the kerf decreased
6. With respect to increase in pulse off-time and weight percentage of alumina surface roughness decreased with increase in surface integrity (Surface finish and texture)

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TABLE 20
ANNOVA TABLE FOR THE FITTED MODELS: (SURFACE ROUGHNESS)

| SOURCE | DEGREES OF FREEDOM | SUM OF SQUARES | MEAN SQUARE | F-RATIO | P-VALUE |
|---|---|---|---|---|---|
| MODEL | **3** | 2.60 | 0.87 | 19.69 | 0.0001 |
| *A-PULSE ON-TIME* | 1 | 1.73 | 1.73 | 39.35 | 0.0001 |
| *B-PULSE OFF-TIME* | 1 | 0.84 | 0.84 | 18.98 | 0.0011 |
| *C-SERVO FEED* | 1 | 0.032 | 0.032 | 0.73 | 0.4105 |

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