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# Modelling and Parametric Analysis of WEDM during Machining of $Tio_2$ Reinforced Aluminium Metal Matrix Composite

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**Abstract—***In this work Parametric Analysis of input parameters of WEDM was analyse during machining on aluminium metal matrix composites. Aluminium metal matrix composites have been fabricated by stir casting by mixing 5 wt % TiO2 as reinforcement in Al7075.To perform the experiment, experimental design has been developed by CCD approach of RSM by considering pulse on time ($T_{on}$=10µs-20µs), Pulse off time ($T_{off}$=5µs-9µs), Current (I= 1Amp-3Amp) and Wire Speed (WS=1-3) as the input parameters by considering Cutting Velocity and Surface Roughness as the output parameters. From Analysis it is found that found that the develop 2nd order regression model for CV and SR are adequate by considering input parameters such as $T_{on}$, $T_{off}$, I and WS. And on increasing $T_{on}$ from 10µs to 15µs CV increases and on further increases 15µs to 20µs it starts decreasing. But SR shows the increasing trends due to increase in $T_{on}$. And on increasing $T_{off}$, CV, and SR both decreases. And on increasing Current 1 to 3 Amp, CV and SR both continuously increases. And on increasing wire Speed CV and SR both decreases.*

**Keywords**: *aluminium metal matrix Composites; Cutting Velocity; surface roughness; WEDM.*

## 1. INTRODUCTION

Composites are materials that combine two or more different materials to create a superior property due to the synergistic effect. They are made up of a matrix phase and a reinforcement phase, and can be made from a variety of materials.[1] Aluminium-based composites (AMCs) are widely used in many sectors due to their unique properties, such as high strength and stiffness, corrosion and oxidation resistance, and low coefficient of thermal expansion. Metal matrix composites (MMCs) are used in important components such as pistons, connecting rods, and turbine blades. The properties of composites depend on various factors, including the volume fraction of reinforcement, processing method, and reinforcement distribution. AMCs reinforced with materials like SiC, $B_4C$, and $TiB_2$ offer improved properties such as higher strength-to-weight ratio, hardness, toughness, thermal stability, and wear and corrosion resistance. The use of composites in various industries has the potential to reduce energy consumption and improve performance. [2] Bharat et. al. fabricated aluminium metal matrix composites by stir casting, reinforced with 3 wt% TiO2 and SiC in matrix AA7178 and conclude that it enhances the tensile strength and hardness of the material [3]. Hussein et al fabricated AMC by powder Metallurgy by mixing 10, 15, 20 and 25 % $TiO_2$ in Al alloy and observed that due increment in TiO2 hardness of AMCs increases.[4]Singh et. al. fabricated aluminium metal matrix composites by mixing 10 Wt % alumina and SiC in Al6061, after that perform experiment on EDM, by using four input parameters such as pulse on time, voltage, current and duty factor, and BBD approach of RSM was used for experimental design and observed that on increasing current at higher pulse on time it increases the MRR.[5] Abhilash et. al. did his experiment on WEDM on Inconel 718, by considering wire feed rate, voltage, pulse on and off time and types of wire electrode as the input parameters. And ANOVA was use to find the significant responses.[6] Tapdar et al. fabricated Magnesium metal matrix composited by using 5wt% SiC and did his experiment on WEDM by considering dielectric flushing pressure, servo feed, pulse on and off time, gap voltage and current as the input parameters and MRR and SR as output parameters. And from ANOVA they were observed that Pulse on and off time were most significant parameters for the MRR and SR. [7] Phate et. al. did his experiment on Aluminium metal matrix composites by WEDM. And experiment was performed by Taguchi L27 orthogonal array by considering pulse on and off, wire feed and current as the input parameters for SR as the response. And found that Pulse on time was the most significant parameter for the SR. And minimum SR (1.8625 micron) achieve at pulse on time (108µs), pulse off time (52µs), wire feed rate (4 m/min) and current (12 A).[8] According to authors knowledge from literature survey it is found that no works reported for parametric analysis of WEDM during machining of TiO2 reinforced aluminium metal matrix composites (AMMCs). So in this work AMMCs was fabricated by stir casting by mixing TiO2 as the reinforced in matrix Al7075. And experiment has been performed on the WEDM by considering Pulse on time, pulse off time, Current and WS as the input parameters for CV and SR as the responses. And CCD approach of RSM was use to experiment design. ANOVA was use to find the significant parameters for the responses

## 2. MATERIALS AND METHOD

### 2.1 Fabrication of metal matrix composites

This paper focuses on the use of Al7075 aluminium alloy as the matrix phase in the production of metal matrix composites (MMCs). Al7075 is a widely used material in various applications due to its high strength, light weight, and excellent anti-corrosion properties, especially in marine industries. The chemical composition and mechanical properties of Al7075 shown in table 1 and 2. The manufacturing methods of MMCs can be broadly categorized into solid phase and liquid phase methods. Several manufacturing methods, including stir casting, powder metallurgy, spray deposition, plasma spraying, squeeze casting, electroplating, and vapour deposition, have been used in recent years to produce MMCs. Among these, stir casting is considered the best process due to its unique properties. Stir casting involves fusing the ceramic particles (reinforcement phase) with liquid melt (matrix) by mechanical stirring and allowing the mixture to solidify. This method is easier and more cost-effective than other manufacturing methods.

**Table 1: Chemical composition of Al7075**

| Elements | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| % | 0.4 | 0.5 | 1.6 | 0.3 | 2.5 | 0.15 | 5.5 | 0.2 | other |

**Table 2: Mechanical Properties of Al7075**

| | |
|---|---|
| Density (g/cm$^3$) | 2.81 |
| Tensile Strength (MPa) | 572 |
| Modulus of elasticity (GPa) | 71.7 |
| Poisson's ratio | 0.33 |
| Melting point (°C) | 477 |

For today's demand, cost-effective high-performance engineering equipment are necessary to develop different MMCs. In this paper, titanium oxide (TiO2) is identified as one of the most exhaustively used reinforcement materials for the fabrication of metal matrix composites (MMCs). Table 3 provides an overview of the basic physical and mechanical properties of TiO2. It can be observed that TiO2 has a very high melting point and strength, which makes it an attractive reinforcement material for MMCs. Other properties of TiO2, such as its hardness, Young's modulus, and thermal conductivity, are also important factors in determining the properties of the resulting MMCs. The use of TiO2 as a reinforcement material in MMCs can lead to improved mechanical properties, such as increased strength, stiffness, and wear resistance. Furthermore, the use of TiO2 in MMCs can also improve their thermal and electrical properties. These properties make TiO2 a suitable material for various applications, including aerospace, automotive, and biomedical engineering. So, addition of this increases the % of titanium oxide into the metal matrix it provides the hard metal matrix along with it also resist high temperature. Whereas with other reinforcement corrosion behaviour cannot be obtain. Aluminium-based composites using titanium oxide reinforcement were fabricated through the stir casting process. The process involved melting Al7075 alloy in a pit furnace crucible, heating it up to 800°C in the furnace. Then, 5 wt.% of reinforcements were added and mixed using a four-bladed stirrer for approximately 10-15 minutes. Prior to adding the reinforcements, they were preheated to a temperature of around 300°C. After thoroughly mixing the reinforcements in the molten metal, the mixture was poured into a mold with dimensions of 100 mm x 80 mm x 10 mm and allowed to cool at room temperature.

**Table 3: Physical and mechanical properties of TiO$_2$**

| | |
|---|---|
| Density(g/cm3) | 4.23 |
| Melting point (°C) | 1843 |
| Boiling Point (°C) | 2972 |
| Thermal conductivity (W/m) | 20-30 |
| Strength (MPa) | 333.3 |

### 2.2 Experimental set-up and process parameters

Wire electrical discharge machining (WEDM) is a popular electro thermal machining process that uses non-stationary electrical discharges to remove material from the work piece. It is effective for machining electrically conductive materials of any hardness, such as aluminium, copper, titanium, and carbide. The process does not involve physical contact between the wire and the work piece, so there is no pressure applied to the work piece as is the case with grinding wheels and milling cutters. This makes it possible to machine small, thin, and fragile parts with minimal clamping pressure, reducing the risk of damage or distortion to the work piece. The study aimed to parametric analysis of machining parameters for the machining of fabricated Aluminium- metal matrix composites reinforced with TiO2 on WEDM. The machining was carried out using a molybdenum wire of 0.25 mm diameter on CNC wire cut EDM (Model no- EX4050C) shown in figure1. The experimental design was based on the central composite design L31 orthogonal array, which considered input parameters such as pulse on time (Ton= 10-20μs), pulse off time (Toff=5-9μs), current (I=1-3Amp), and wire speed (WS=1-3). The speed of wire at level 1 are 10.4m/sec and level 2, 6.76 m/sec and at level 3, 3.12m/sec. Pilot tests were performed to determine the appropriate levels of input parameters for the experiments, which were repeated three times to reduce variability and uncertainties.

**Figure 1: WEDM**

**Table 4: Input parameters and their levels**

| Parameters | units | Low | Medium | High |
|---|---|---|---|---|
| Pulse on | µs | 10 | 15 | 20 |
| Pulse off | µs | 5 | 7 | 9 |
| Current | Amp | 1 | 2 | 3 |
| Wire speed |  | 1 | 2 | 3 |

**Table 5: Observation table for machining of AMMC using molybdenum wire**

| Expt. No. | Ton (µs) | Toff (µs) | I (Amp) | WS | (CV) (mm/min) | SR (µm) |
|---|---|---|---|---|---|---|
| 1 | 10 | 5 | 1 | 1 | 1.0752 | 3.635 |
| 2 | 20 | 5 | 1 | 1 | 3.1806 | 4.6625 |
| 3 | 10 | 9 | 1 | 1 | 1.6686 | 3.76 |
| 4 | 20 | 9 | 1 | 1 | 2.2758 | 4.2325 |
| 5 | 10 | 5 | 3 | 1 | 4.9806 | 3.625 |
| 6 | 20 | 5 | 3 | 1 | 4.9998 | 4.4375 |
| 7 | 10 | 9 | 3 | 1 | 4.6314 | 3.76 |
| 8 | 20 | 9 | 3 | 1 | 5.019 | 4.4125 |
| 9 | 10 | 5 | 1 | 3 | 2.2872 | 3.1425 |
| 10 | 20 | 5 | 1 | 3 | 2.8692 | 3.71 |
| 11 | 10 | 9 | 1 | 3 | 1.3746 | 3.54 |
| 12 | 20 | 9 | 1 | 3 | 1.7142 | 3.35 |
| 13 | 10 | 5 | 3 | 3 | 5.8662 | 3.3725 |
| 14 | 20 | 5 | 3 | 3 | 6 | 4.3475 |
| 15 | 10 | 9 | 3 | 3 | 4.5048 | 3.405 |
| 16 | 20 | 9 | 3 | 3 | 5.4096 | 4.35 |
| 17 | 10 | 7 | 2 | 2 | 4.2168 | 3.395 |
| 18 | 20 | 7 | 2 | 2 | 1.2162 | 4.14 |
| 19 | 15 | 5 | 2 | 2 | 5.739 | 3.785 |
| 20 | 15 | 9 | 2 | 2 | 4.1904 | 3.91 |
| 21 | 15 | 7 | 1 | 2 | 2.5284 | 3.605 |
| 22 | 15 | 7 | 1 | 2 | 5.6892 | 4.255 |
| 23 | 15 | 7 | 2 | 1 | 5.0766 | 4.3275 |
| 24 | 15 | 7 | 2 | 3 | 4.6314 | 3.67 |
| 25 | 15 | 7 | 2 | 2 | 5.0766 | 3.6 |
| 26 | 15 | 7 | 2 | 2 | 4.9998 | 3.7725 |
| 27 | 15 | 7 | 2 | 2 | 4.4892 | 3.675 |
| 28 | 15 | 7 | 2 | 2 | 4.6314 | 3.4675 |
| 29 | 15 | 7 | 2 | 2 | 4.8174 | 3.5075 |
| 30 | 15 | 7 | 2 | 2 | 4.8348 | 4.0225 |
| 31 | 15 | 7 | 2 | 2 | 4.8888 | 3.7875 |

### 2.3 Measurement

Since in this work two responses were taken ie. Cutting velocity (CV) and Surface Roughness (SR). To perform the experiment a slot of 10x1mm of 10mm thickness were cut. Then total cut distance by WEDM during machining was (1+10+1=21 mm) 21mm. So, the CV was calculated by ratio of total distance travel by the tool to cut the work piece to total time during machining.

$$\text{CV (mm/min)} = \frac{\mathit{total\ distance\ move\ by\ the\ tool\ to\ cut\ the\ workpiece}}{\mathit{total\ time\ to\ macining}\ (\mathit{min})} \qquad (1)$$

Surface roughness, which refers to the deviations in the surface texture of a material, can have a significant impact on the mechanical properties and functional attributes of machine components. It can affect properties such as fatigue behaviour, corrosion resistance, creep life, friction, wear, light reflection, heat transmission, and lubrication. The surface roughness can be influenced by several factors such as machining parameters, work-piece materials, cutting tool properties, and cutting phenomenon. In this study, the surface roughness was evaluated using the Ra measure and cutting velocity was also considered as a performance characteristic. The measurements were taken using a TAYLOR HOBSON surtronic s 128 test instrument with a cut-off of 5.6 mm. Three surface roughness measurements were taken and an average of these values was used for analysis.

## 3. RESPONSE SURFACE MODELLING

RSM is a powerful tool for modelling the relationship between input parameters and output variables in complex systems. It can help researchers to optimize processes and products by identifying the most important input parameters and their optimal values. CCD and BBD are two types of experimental designs that are often used in RSM. CCD is preferred over BBD due to its ability to explore a wider range of input parameter settings, including extreme settings, and its higher quantity of design points at the outside of the cube (axial points). By using CCD, researchers can obtain a more accurate and complete understanding of the relationship between input parameters and output variables, which can lead to more efficient and effective processes and products. Overall, RSM and its associated experimental designs are valuable tools for data analysis, modelling, and optimization in a variety of fields, including engineering, chemistry, and biology. To develop the RSM model, and experiments were performed at different levels of input parameters, which are shown in Table 5. The second-order regression model is used to establish the relationship between cutting velocity and surface roughness. The general expressions for the second-order regression model for cutting velocity and surface roughness are shown in Eq. 2 and Eq. 3, respectively. The observed data from the set of experiments shown in Table 5 were used as inputs to MINITAB software to establish the RSM model. The prediction capability of the regression model is quite stable due to its rotability, and the variance occurred is within the experimental domain. In other words, RSM is a useful tool to determine the relationship between input parameters and output variables, and CCD is a preferred design for RSM due to its flexibility and ability to explore a wide range of input parameter combinations.

### 3.1 RSM Models for Cutting velocity of AMMC

The following equation 2 show the 2nd order regression model for the CV. And table 6 show the ANOVA for CV from table it is found that the p value of model is less than 0.05 so, model is significant. And p value of current is less than 0.05 so it is significant. Since Current is significant for the CV then we see the Combine Effect of Current with respect to other input parameters. So, the effect of current with Ton, Toff and WS are shown in figure 2. And table 7 show the model summary for CV since R-sq and R-sq(adj) value are 87.78% and 77.10% respectively, so develop regression model for CV are significant.[9]

$$CV=-8.63 + 2.181\ T_{on} - 1.81\ T_{off} + 2.94\ I - 0.93\ WS - 0.0683\ T_{on}\times T_{on} + 0.135\ T_{off}\times T_{off} - 0.314\ I\times I + 0.431\ WS\times WS - 0.0038\ T_{on}\times T_{off} - 0.0274\ T_{on}\times I - 0.0145\ T_{on}\times WS + 0.0030\ T_{off}\times I - 0.1056\ T_{off}\times WS + 0.132\ I\times WS \tag{2}$$

**Table 6: ANOVA for cutting velocity of AMMC using the molybdenum wire**

| Source | DF | F-Value | P-Value |
|---|---|---|---|
| Model | 14 | 8.21 | 0.000 |
| Linear | 4 | 21.93 | 0.000 |
| $T_{on}$ | 1 | 0.45 | 0.511 |
| $T_{off}$ | 1 | 4.04 | 0.062 |
| I | 1 | 82.89 | 0.000 |
| WS | 1 | 0.32 | 0.579 |
| Square | 4 | 6.16 | 0.003 |
| $T_{on}\times T_{on}$ | 1 | 14.25 | 0.002 |
| $T_{off}\times T_{off}$ | 1 | 1.44 | 0.248 |
| I×I | 1 | 0.48 | 0.497 |
| WS×WS | 1 | 0.91 | 0.354 |
| 2-Way Interaction | 6 | 0.44 | 0.842 |
| $T_{on}\times T_{off}$ | 1 | 0.04 | 0.839 |
| $T_{on}\times I$ | 1 | 0.56 | 0.463 |
| $T_{on}\times WS$ | 1 | 0.16 | 0.696 |
| $T_{off}\times I$ | 1 | 0.00 | 0.974 |
| $T_{off}\times WS$ | 1 | 1.35 | 0.263 |
| I×WS | 1 | 0.52 | 0.480 |

**Table 7: Model Summary for cutting velocity of alumina based MMC**

| S | R-sq | R-sq(adj) |
|---|---|---|
| 0.728164 | 87.78% | 77.19% |

### 3.2 RSM Models for Surface roughness of AMMC

The following equation 3 show the 2nd order regression model for the SR. And table 7 show the ANOVA for SR from table it is found that the p value of model is less than 0.05 so, model is significant. And p value of $T_{on}$, current and WS are less than 0.05 so it is significant. Since Current is significant for the SR then we see the Combine Effect of Current with respect to other input parameters. So, the effect of current with Ton, Toff and WS are shown in figure 3(a, b and c). And table 9 show the model summary for SR since R-sq and R-sq (adj) value are 84.4% and 70.74% respectively, so develop regression model for SR are significant.

$$SR = 2.85 + 0.223\ T_{on} + 0.144\ T_{off} - 0.745\ I - 0.930\ WS - 0.00372\ T_{on}\times T_{on} - 0.0033\ T_{off}\times T_{off} + 0.069\ I\times I + 0.138\ WS\times WS - 0.00939\ T_{on}\times T_{off} + 0.0188\ T_{on}\times I - 0.0083\ T_{on}\times WS + 0.0129\ T_{off}\times I + 0.0084\ T_{off}\times WS + 0.1117\ I\times WS \tag{3}$$

**Table 8. ANOVA for SR of AMMC using the Molybdenum wire**

| Source | DF | F-Value | P-Value |
|---|---|---|---|
| Model | 14 | 6.18 | 0.000 |
| Linear | 4 | 17.97 | 0.000 |
| $T_{on}$ | 1 | 45.33 | 0.000 |
| $T_{off}$ | 1 | 0.00 | 0.998 |
| I | 1 | 6.80 | 0.019 |
| WS | 1 | 19.75 | 0.000 |
| Square | 4 | 0.69 | 0.608 |
| $T_{on}\times T_{on}$ | 1 | 0.51 | 0.486 |
| $T_{off}\times T_{off}$ | 1 | 0.01 | 0.921 |
| I×I | 1 | 0.28 | 0.602 |
| WS×WS | 1 | 1.12 | 0.306 |
| 2-Way Interaction | 6 | 1.98 | 0.129 |
| $T_{on}\times T_{off}$ | 1 | 3.19 | 0.093 |
| $T_{on}\times I$ | 1 | 3.21 | 0.092 |
| $T_{on}\times WS$ | 1 | 0.63 | 0.439 |
| $T_{off}\times I$ | 1 | 0.24 | 0.631 |

| | | | |
|---|---|---|---|
| $T_{off}$×WS | 1 | 0.10 | 0.755 |
| I×WS | 1 | 4.51 | 0.050 |

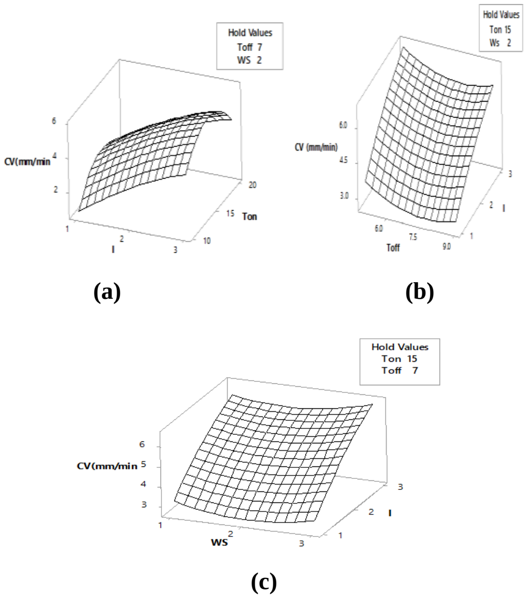
**Table 9: Model Summary for SR of AMMC using the**

| S | R-sq | R-sq(adj) |
|---|---|---|
| 0.210313 | 84.40% | 70.74% |

## 4. RESULTS AND DISCUSSIONS:

### 4.1. Parametric Analysis of AMMCs using molybdenum wire

For cutting velocity, increasing Ton from 10 µs to 15 µs at I=1 resulted in a 66% increase in cutting velocity, which suggests that increasing Ton can have a positive effect on cutting velocity, up to a certain point. However, when Ton was further increased to 20 µs, cutting velocity decreased by 50%. when I was increased from 1 to 3 at Ton=10 µs, cutting velocity increased two-fold, Similarly, when I was increased from 1 to 3 at Ton=20 µs, cutting velocity increased by 57%.From fig2 (b) when we increase $T_{off}$ from 5 µs to 7µs at I=1the cutting velocity start decreasing 64% but at I=1, $T_{off}$ is vary from 5 µs to 7µs so it start increasing at a same rate as its decreasing and when I increase from 1 to 3 at $T_{off}$=5, cutting velocity increase by one times. From fig2 (c) when the wire speed increases from 1 to 2 at I=1, the cutting velocity decreases by 50%. However, when the wire speed increases from 2 to 3, the cutting velocity starts increasing by 83%. And if the current is increased from 1 to 3 at wire speed 1, the cutting velocity increases by one times. it appears that increasing the wire speed has a non-linear effect on cutting velocity. Similarly, increasing the current at a fixed wire speed can also lead to an increase in cutting velocity.

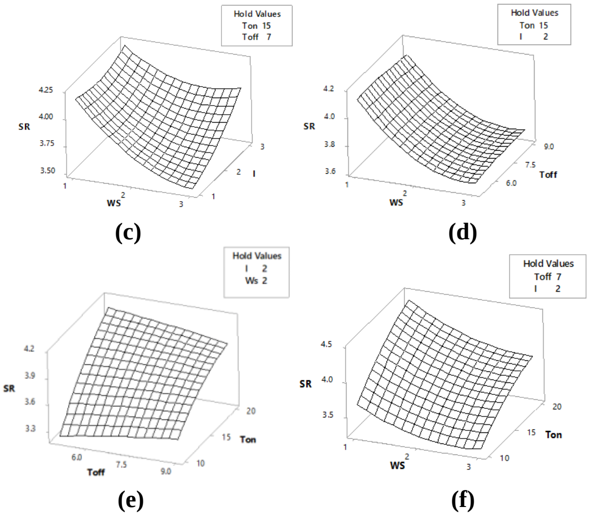


(a) (b)

(c)

**Fig. 2: Variation of Cutting velocity using molybdenum wire with (a) $T_{on}$ and current (b) Toff and current (c) WS and current**

For surface roughness, fig 3(a) when Toff increases from 5 µs to 9 µs at I=2, the surface roughness decreases at a rate of 26%. This suggests that a longer Toff time results in a smoother surface finish. However, when the current increases from 1 to 3 at Toff=5 µs, the surface roughness is increasing at a rate of 3.4%. it suggests that a higher current can lead to a rougher surface finish. From fig 3 (b) when I increases from 1 to 2 at Ton=15 µs, the surface roughness starts decreasing at a rate of 1.8%.However, when Ton is increasing from 10 µs to 20 µs at I=1, the surface roughness is increasing at a rate of 22%. From fig 3 (c) when wire speed increases from 1 to 3 at I=2, the surface roughness increases by about 9.6%.However, when I increases from 1 to 3 at wire speed 3, the surface roughness starts increasing at a rate of 18%. From fig 3(d) when the wire speed is at its minimum, the surface roughness is at its maximum. However, as the wire speed increases from 1 to 3, the surface roughness continuously decreases. Regarding Toff, it normally decreases but with respect to wire speed, Toff continuously increases and surface roughness also increases. This suggests that increasing Toff time with increasing wire speed can result in a rougher surface finish. From fig 3 (e) when ton is increased from 10µs to 15µs at Toff 7µs, surface roughness starts increasing at a rate of 22%.but, when Toff is increased from 5µs to 9µs at ton 10µs, surface roughness also increases at a rate of 12%. From fig 3 (f) when wire speed is increased from 1 to 3 at ton 10 µs, surface roughness starts decreasing at the rate of 9%.while, when ton is increased from 10 µs to 20 µs at wire speed 2, surface roughness increases by 22%.



(c) (d)

(e) (f)

**Fig. 3: Variation of surface roughness using molybdenum wire with (a) $T_{on}$ and current (b) $T_{on}$ time and current (c) wire speed and current (d) wire speed and $T_{off}$ (e) $T_{off}$ and $T_{on}$ (f) wire speed and $T_{on}$**

## 5. CONCLUSIONS

In this work Aluminium metal matrix composites has been prepared by mixing 5 % TiO2 in Al7075 by stir casting process. After that Experimental work has been done on WEDM, and experimentation was designed by CCD approach of RSM. To perform the experiment there was four input parameters such as Ton, Toff, I and WS was consider for CV and SR as output response. After Analysis there was some conclusion has been found.

i. The develop 2nd order regression model for CV and SR are adequate by considering input parameters such as $T_{on}$, $T_{off}$, I and WS.
ii. On increasing Ton 10µs to 15µs CV increases and on further increases 15µs to 20µs it starts decreasing. But SR shows the increasing trends due to increase in $T_{on}$.
iii. On increasing $T_{off,}$ both CV and SR decreases.
iv. On increasing Current 1 to 3 Amp, both CV and SR continuously increases.
v. On increasing wire Speed CV and SR both decreases.

## 6. ACKNOWLEDGMENT

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