# Experimental and Parametric Study on Wire EDM of Solid-Lubricant Reinforced Copper Composites

**Logeshkumar S[1], Ramesh C[2], NV Dhandapani S[3] , Sudhakar S [4]**

[1] *Post Graduate Student, Department of Mechanical Engineering, KIT-Kalaignarkarunanidhi Institute of Technology, Coimbatore, India*
[2] *Professor, Department of Mechanical Engineering, KIT-Kalaignarkarunanidhi Institute of Technology, Coimbatore, India*
[3] *Professor, Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore, India*
[4] *Professor, Department of Mechanical Engineering, KIT-Kalaignarkarunanidhi Institute of Technology, Coimbatore, India*

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## Abstract-

*This research presents a detailed experimental investigation on Copper–$MoS_2$ Metal Matrix Composites fabricated using powder metallurgy and machined using Wire Electrical Discharge Machining (WEDM). Copper is widely used due to its conductivity but suffers from poor wear resistance and machinability. To overcome these limitations, $MoS_2$ is used as reinforcement due to its solid lubricating behavior. Composites with varying reinforcement percentages (0%, 2%, 4%, and 6%) are fabricated. The machining performance is analyzed by varying pulse OzN time, pulse OFF time, and discharge current. The responses measured include Material Removal Rate (MRR) and Surface Roughness (Ra). Results show that $MoS_2$ significantly improves machinability and surface quality due to lubrication effect. However, excessive reinforcement reduces MRR. The study concludes that 4% $MoS_2$ provides optimal performance.*

***Keywords:*** *MMC, Copper, $MoS_2$, Powder Metallurgy, WEDM, Surface Roughness, MRR*

## 1.1 METAL MATRIX COMPOSITES

Metal Matrix Composites (MMCs) are engineered materials consisting of a metal matrix combined with reinforcement particles such as ceramics or solid lubricants. The matrix provides ductility and toughness, while reinforcement enhances strength, hardness, and wear resistance. MMCs overcome limitations of conventional metals like low wear resistance and thermal instability. They are widely used in aerospace, automotive, and thermal applications where high performance is required. The effectiveness of MMCs depends on uniform distribution of reinforcement and strong interfacial bonding. Proper fabrication techniques ensure improved load transfer and structural integrity, making MMCs suitable for advanced engineering applications.

### 1.2 COPPER MATRIX COMPOSITES

Copper Matrix Composites (CuMMCs) are developed to improve the mechanical limitations of pure copper while retaining its excellent electrical and thermal conductivity. Pure copper has low hardness and poor wear resistance, making it unsuitable for heavy-duty applications. By incorporating reinforcements such as $MoS_2$, the composite gains improved lubrication, reduced friction, and better machinability. $MoS_2$ acts as a solid lubricant, forming a protective layer that reduces tool wear and improves surface finish. CuMMCs are widely used in electrical contacts, heat exchangers, and EDM electrodes where both conductivity and strength are required.

### 1.3 FABRICATION METHODS OF MMC

MMCs can be fabricated using liquid-state and solid-state methods. Liquid-state methods such as stir casting are economical but may lead to non-uniform distribution and reinforcement degradation. Solid-state methods like powder metallurgy are preferred for temperature-sensitive reinforcements. These methods provide better control over composition, uniform particle distribution, and improved bonding. The choice of fabrication technique directly influences density, strength, and microstructural properties of the composite. Therefore, selecting an appropriate method is critical for achieving desired performance.

### 1.4 POWDER METALLURGY

Powder metallurgy is a solid-state fabrication technique involving mixing, compaction, and sintering of powders. It allows precise control over reinforcement percentage and ensures uniform distribution within the matrix. Since the process occurs below melting temperature, it prevents degradation of reinforcements like $MoS_2$. Sintering enhances bonding through diffusion, resulting in improved strength and density. This method also reduces material wastage and supports near-net shape manufacturing. Powder metallurgy is widely used for producing high-quality copper-based composites with enhanced properties.

### 1.5 NON-CONVENTIONAL MACHINING

Non-conventional machining processes remove material using electrical, thermal, or chemical energy instead of mechanical cutting. These processes are essential for machining hard materials like MMCs, where conventional tools experience excessive wear. EDM and WEDM are commonly used methods that provide high precision and minimal tool wear. They eliminate cutting forces and allow machining of complex geometries. These techniques ensure better surface finish and dimensional accuracy, making them suitable for advanced materials.

### 1.6 WIRE ELECTRICAL DISCHARGE MACHINING

Wire Electrical Discharge Machining (WEDM) is a precision machining process that uses electrical sparks to remove material from conductive workpieces. A continuously moving wire electrode generates sparks that melt and vaporize material. The absence of physical contact reduces tool wear and enables machining of hard and brittle materials. WEDM is widely used for producing intricate shapes with high accuracy. It is especially effective for machining MMCs due to its non-contact nature and superior surface finish

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## CHAPTER 2: LITERATURE REVIEW

Studies on MMCs indicate significant improvement in mechanical and tribological properties with reinforcement addition. Researchers found that $MoS_2$ enhances lubrication and reduces friction, improving machinability. Powder metallurgy is widely adopted for uniform reinforcement distribution and better bonding. EDM and WEDM are effective for machining MMCs, offering high precision and reduced tool wear. However, optimization of machining parameters remains a key research area to achieve better performance.

### 3.1 METHODOLOGY

The methodology includes selection of materials, powder blending, compaction, sintering, and machining. Copper and $MoS_2$ powders are mixed to achieve uniform distribution, then compacted and sintered to form composites. Machining is performed using WEDM to evaluate performance. Process parameters are varied systematically to study their effect on machining characteristics such as surface finish and material removal rate.

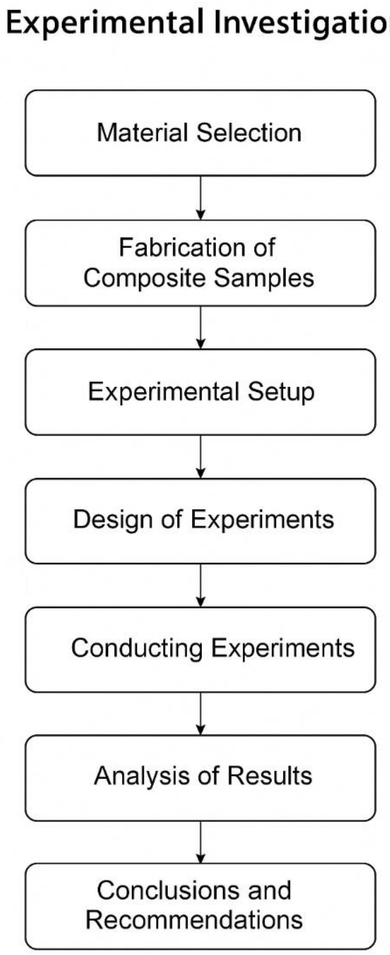


**Fig. 1 Methodology Flow Chart of Experimental Investigation**

### 3.2 COPPER PROPERTIES

Copper is widely used due to its high electrical and thermal conductivity. It also offers good corrosion resistance and ductility. However, its low hardness and poor wear resistance limit its application in mechanical environments. Reinforcing copper with suitable materials improves its strength and tribological properties while maintaining its conductivity advantages.

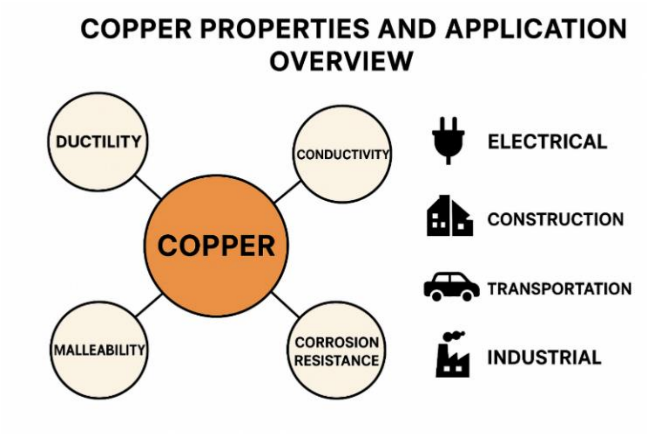


**Fig. 2 Copper Properties and Applications Overview Diagram**

### 3.3 REINFORCEMENT MATERIAL PROPERTIES

Reinforcement materials play a key role in improving composite performance. $MoS_2$ is selected due to its solid lubricating properties, which reduce friction and enhance machinability. Proper selection of reinforcement ensures better bonding and uniform distribution, leading to improved mechanical and tribological behavior.

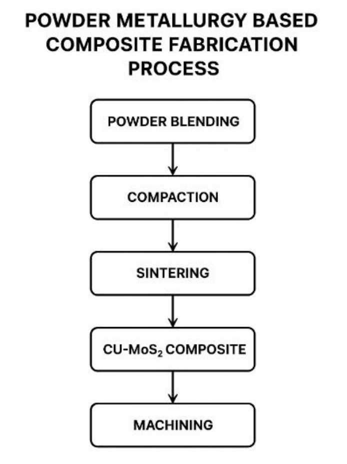


**Fig. 3 Powder Metallurgy-Based Composite Fabrication Process Flow (Cu–$MoS_2$)**

### 3.4 COMPOSITE FABRICATION

Composite fabrication is carried out using powder metallurgy to ensure uniform mixing and strong bonding. The process involves blending copper and $MoS_2$ powders, followed by compaction and sintering. This results in improved density, strength, and wear resistance. Proper fabrication ensures consistent performance of the composite material.

**Table:1 - Composite Fabrication**

| Sl. No. | Parameter | Details |
|---|---|---|
| 1 | Base Material | Copper (Cu) |
| 2 | Reinforcement Material | Molybdenum Disulfide ($MoS_2$) |
| 3 | Reinforcement % | 0%, 2%, 4%, 6% |
| 4 | Fabrication Method | Powder Metallurgy |

### 3.5 PROCESS PARAMETERS OF WEDM

WEDM performance is influenced by parameters such as pulse-on time, pulse-off time, current, wire feed, and voltage. These parameters control spark energy and affect material removal rate, surface roughness, and dimensional accuracy. Proper optimization of these parameters is essential for achieving efficient machining and improved surface quality.

**Table:2- Factors for Analysis: Reinforcement %, Current, pulse ON time, pulse OFF time**

| Sl. No | Control Factors | Symbol | Unit | Level I | Level I | Level III | Level IV |
|---|---|---|---|---|---|---|---|
| 1 | Reinforcement% | R | % | 0 | 2 | 4 | 6 |
| 2 | Pulse ON Time | PON | µs | 120 | 125 | 130 | 135 |
| 3 | Pulse OFF Time | POFF | µs | 40 | 45 | 50 | 55 |
| 4 | Wire Feed Rate | WFR | m/min | 5 | 6 | 7 | 8 |

### 3.6 EXPERIMENTAL DESIGN

Experimental design is used to systematically analyze the effect of process parameters on machining performance. Techniques such as Taguchi method help reduce the number of experiments while maintaining accuracy. Parameters are varied at different levels, and responses such as material removal rate and surface roughness are measured to determine optimal conditions.

## CHAPTER 4: RESULTS AND DISCUSSION

*The experimental results indicate that reinforcement percentage and machining parameters significantly influence performance. Increased* $MoS_2$ *content improves surface finish due to lubrication but may reduce material removal rate. Higher pulse-on time increases MRR but worsens surface roughness. Optimal parameter combination provides a balance between productivity and surface quality. Statistical analysis confirms the influence of key parameters on machining behavior.*

### 4.1 Experimental Results Overview

*The WEDM experiments were conducted according to the Taguchi L16 orthogonal array by varying Reinforcement percentage (0%, 2%, 4%, 6%), Pulse ON Time (120–135 µs), Pulse OFF Time (40–55 µs), and Wire Feed Rate (5–8 m/min). The measured responses were Surface Roughness (Ra) and Material Removal Rate (MRR). Surface Roughness ranged from 2.78 µm to 3.17 µm and MRR ranged from 8.07* $mm^3$*/min to 18.55* $mm^3$*/min.*

**Table 4. Results for Surface Roughness and MRR**

| Reinforcement% | PON | POFF | WireFeed | Surface Roughness | MRR |
|---|---|---|---|---|---|
| 0 | 120 | 40 | 5 | 2.83 | 12.68 |
| 0 | 125 | 45 | 6 | 2.82 | 17.47 |
| 0 | 130 | 50 | 7 | 2.94 | 17.14 |
| 0 | 135 | 55 | 8 | 2.93 | 17.21 |
| 2 | 120 | 45 | 7 | 2.82 | 14.07 |
| 2 | 125 | 40 | 8 | 2.89 | 18.55 |
| 2 | 130 | 55 | 5 | 2.96 | 17.19 |
| 2 | 135 | 50 | 6 | 2.95 | 17.20 |
| 4 | 120 | 50 | 8 | 2.78 | 8.88 |
| 4 | 125 | 55 | 7 | 2.78 | 10.62 |
| 4 | 130 | 40 | 6 | 3.08 | 17.5 |
| 4 | 135 | 45 | 5 | 3.09 | 15.09 |
| 6 | 120 | 55 | 6 | 2.99 | 9.62 |
| 6 | 125 | 50 | 5 | 2.83 | 8.07 |
| 6 | 130 | 45 | 8 | 3.12 | 12.58 |
| 6 | 135 | 40 | 7 | 3.17 | 15.08 |

### 4.2 S/N Ratio Analysis for Surface Roughness

*Using the Smaller-the-better criterion, Pulse ON Time was identified as the most significant parameter influencing surface roughness, followed by reinforcement percentage, Pulse OFF Time, and Wire Feed Rate. Increasing Pulse ON Time increases spark energy and crater depth, resulting in higher surface roughness.*

### Table 4.2 S/N Ratio Response Table for Surface Roughness

| Level | Reinforcement % | PON | POFF | Wire Feed |
|---|---|---|---|---|
| 1 | -9.231 | -9.096 | -9.51 | -9.283 |
| 2 | -9.291 | -9.187 | -9.412 | -9.452 |
| 3 | -9.369 | -9.604 | -9.343 | -9.401 |
| 4 | -9.629 | -9.632 | -9.255 | -9.384 |
| Delta | 0.398 | 0.536 | 0.256 | 0.169 |
| Rank | 2 | 1 | 3 | 4 |

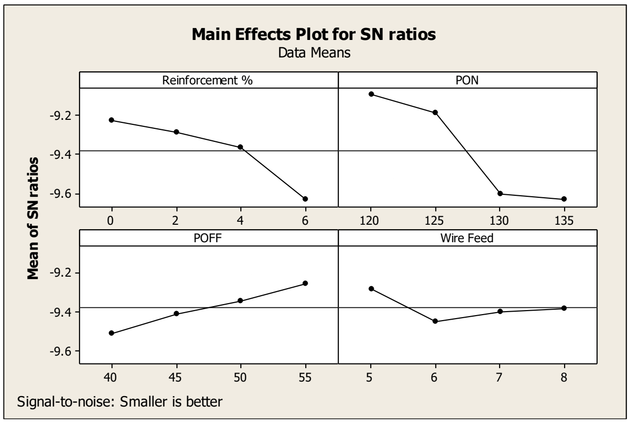


Figure 4.1 Main Effect Plot for Surface Roughness

### 4.3 ANOVA for Surface Roughness

*ANOVA results indicate that all parameters are statistically significant (P < 0.05). Pulse ON Time shows the highest F-value, confirming dominant influence. The statistical model exhibits high reliability with* $R^2 \approx 99\%$

### Table 4.3 ANOVA Results for Surface Roughness

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Reinforcement % | 3 | 0.044225 | 0.044225 | 0.014742 | 84.24 | 0.002 |
| PON | 3 | 0.107625 | 0.107625 | 0.035875 | 205 | 0.001 |
| POFF | 3 | 0.017475 | 0.017475 | 0.005825 | 33.29 | 0.008 |
| Wire Feed | 3 | 0.007125 | 0.007125 | 0.002375 | 13.57 | 0.03 |
| Error | 3 | 0.000525 | 0.000525 | 0.000175 | | |
| Total | 15 | 0.176975 | | | | |

### 4.4 Main Effect Plot for Surface Roughness

The main effect plot shows that surface roughness increases with Pulse ON Time and reinforcement percentage, decreases with Pulse OFF Time, and shows minimal variation with Wire Feed Rate.

### 4.5 Regression Model for Surface Roughness

Ra = 1.3425 + 0.022R + 0.0138PON − 0.0059POFF + 0.009WFR. The positive coefficients of reinforcement and Pulse ON Time indicate increasing roughness, while higher Pulse OFF Time improves surface finish.

### Table 4.5 Regression Coefficients for Surface Roughness

| |
|---|
| S = 0.0132288 R-Sq = 99.70% R-Sq(adj) = 98.52% |
| Regression Equation: |
| Surface Roughness = 1.3425 + 0.022 Reinforcement % + 0.0138 PON - 0.0059 POFF + 0.009 Wire Feed |
| S = 0.0467197 R-Sq = 86.43% R-Sq(adj) = 81.50% R-Sq(pred) = 71.50% |

### Figure 4.3 Residual Plot for Surface Roughness

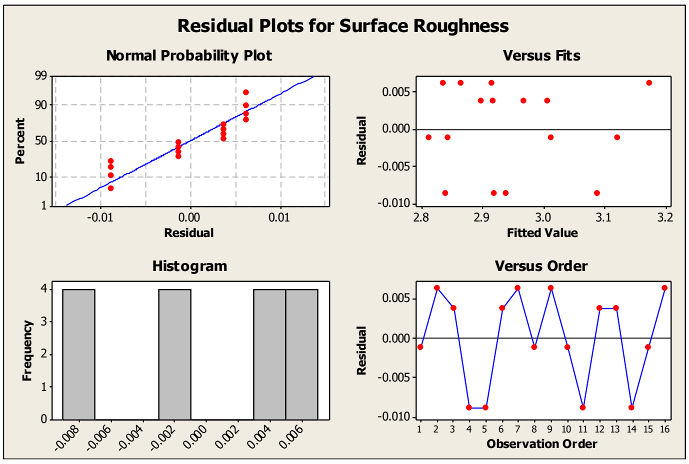


**Figure 4.4 Contour Plots of Ra vs Reinforcement% , PON**

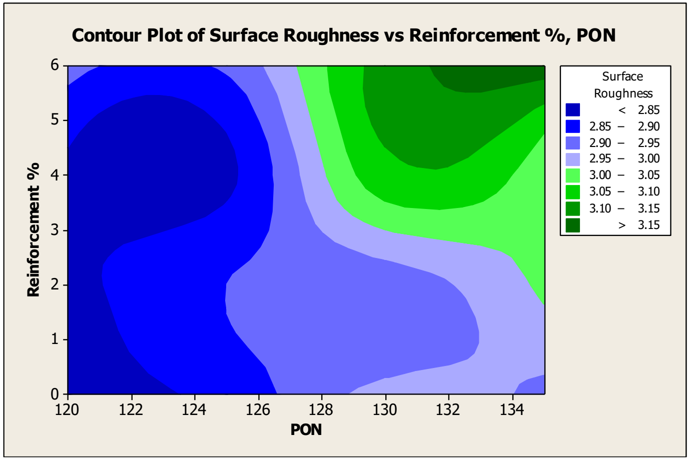


**Figure 4.5 Contour Plots of Ra vs PON , POFF**

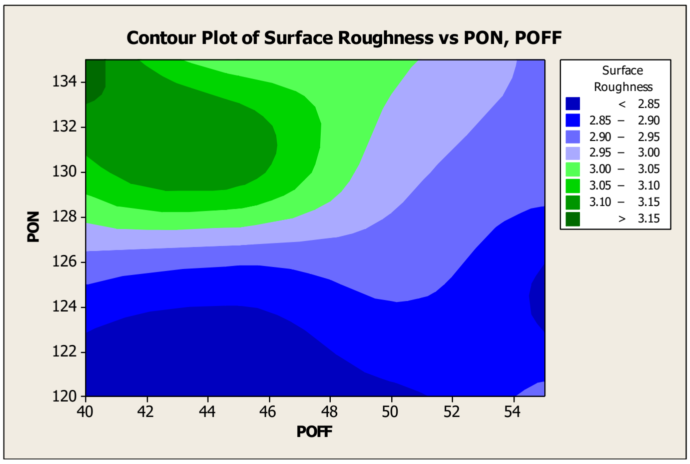
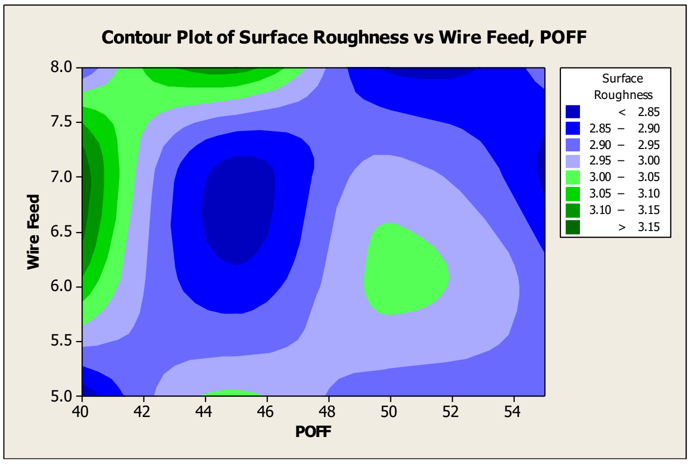


**Figure 4.6 Contour Plots of Ra vs Wire Feed , POFF**



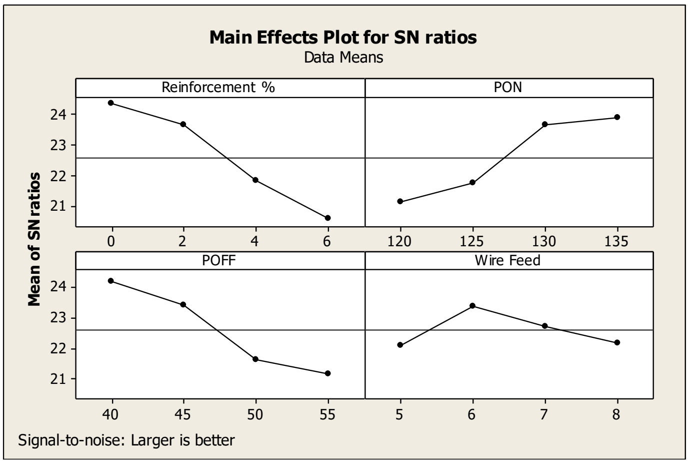
## 4.6 S/N Ratio Analysis for MRR

Using the Larger-the-better criterion, reinforcement percentage was identified as the most significant factor affecting MRR. Increasing reinforcement reduces electrical conductivity, thereby reducing spark efficiency and MRR.

**Table 4.5 S/N Ratio Response Table for MRR**

| Level | Reinforcement % | PON | POFF | Wire Feed |
|---|---|---|---|---|
| 1 | 24.33 | 21.11 | 24.17 | 22.09 |
| 2 | 23.63 | 21.75 | 23.41 | 23.38 |
| 3 | 21.83 | 23.63 | 21.63 | 22.71 |
| 4 | 20.58 | 23.88 | 21.16 | 22.18 |
| Delta | 3.75 | 2.76 | 3.02 | 1.3 |
| Rank | 1 | 3 | 2 | 4 |

**Figure 4.7 S/N Ratio Plot for MRR**



## 4.7 ANOVA for MRR

ANOVA confirms all parameters significantly influence MRR ($P < 0.05$). Reinforcement percentage has the highest contribution with model reliability $R^2 \approx 99\%$.

## Table 4.6 ANOVA Results for MRR

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Reinforcement % | 3 | 70.623 | 70.623 | 23.541 | 164.85 | 0.001 |
| PON | 3 | 42.335 | 42.335 | 14.112 | 98.82 | 0.002 |
| POFF | 3 | 48.445 | 48.445 | 16.148 | 113.08 | 0.001 |
| Wire Feed | 3 | 13.786 | 13.786 | 4.595 | 32.18 | 0.009 |
| Error | 3 | 0.428 | 0.428 | 0.143 | | |
| Total | 15 | 175.617 | | | | |

### 4.8 Main Effect Plot for MRR

*MRR decreases with increasing reinforcement percentage and Pulse OFF Time, while it increases with Pulse ON Time. Wire Feed Rate shows comparatively minor influence.*

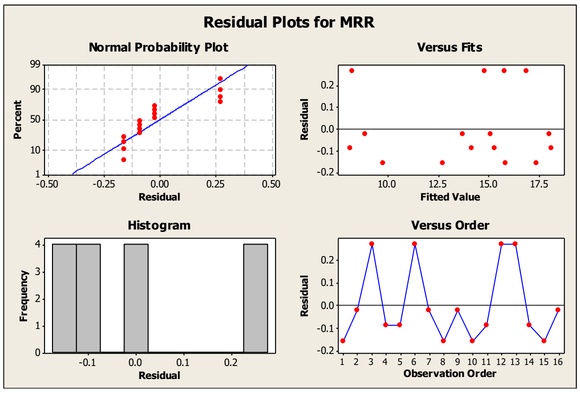
### 4.9 Regression Model for MRR

*MRR = −3.47663 − 0.9336R + 0.28025PON − 0.30895POFF − 0.13075WFR. Higher Pulse ON Time increases MRR, whereas higher reinforcement and Pulse OFF Time decrease MRR.*

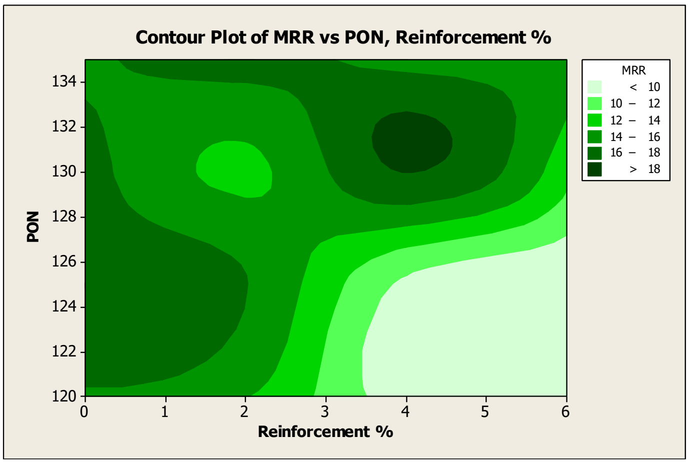
## Table 4.7 Regression Coefficients for MRR

| |
|---|
| *S = 0.377897 R-Sq = 99.76% R-Sq(adj) = 98.78%* |
| *MRR = -3.47663 - 0.933625 Reinforcement % + 0.28025 PON - 0.30895 POFF - 0.13075 Wire Feed* |
| *S = 1.29853 R-Sq = 89.44% R-Sq(adj) = 85.60% R-Sq(pred) = 74.12%* |

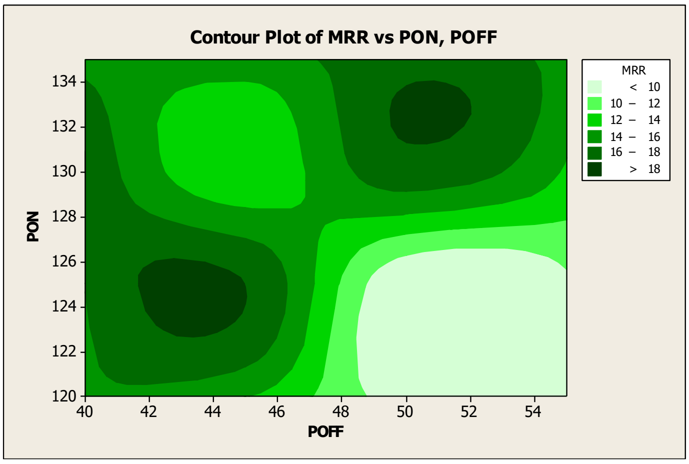
## Figure 4.8 Residual Plot for MRR



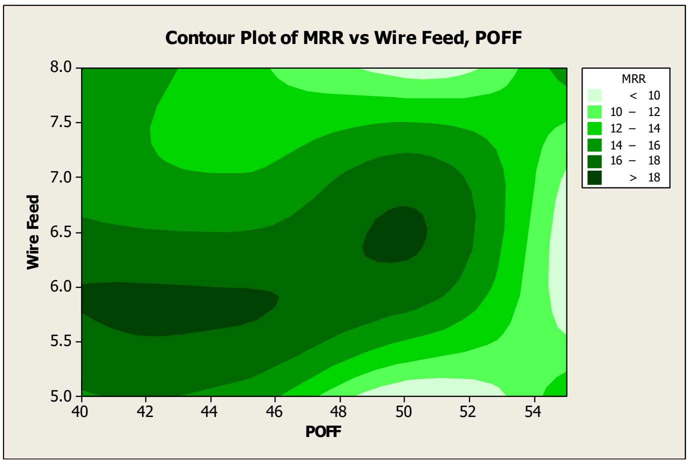
## Figure 4.9 Contour Plot of MRR vs PON , Reinforcement %



## Figure 4.10 Contour Plot of MRR vs PON , POFF



## Figure 4.10 Contour Plot of MRR vs Wire feed, POFF



## 4.10 Confirmation Test and Validation

Optimal machining parameters were selected based on S/N ratio analysis. Confirmation experiments showed that predicted and experimental values were in close agreement, validating the regression models.

## 4.11 Interaction Effect Analysis

Interaction analysis revealed that reinforcement percentage and Pulse ON Time significantly influence MRR. Proper combination of Pulse ON and Pulse OFF Time ensures stable machining.

## 4.12 Comparative Discussion

The results align with previous copper-based EDM/WEDM studies. $MoS_2$ reinforcement reduces MRR but improves surface integrity compared to unreinforced copper.

## 4.13 Summary of Results

Pulse ON Time is dominant for Surface Roughness, while reinforcement percentage dominates MRR. Increasing $MoS_2$ reduces MRR and higher Pulse ON Time increases both MRR and surface roughness. Statistical models show strong predictive capability.

## CHAPTER 5: CONCLUSION AND FUTURE WORK

The study concludes that $Cu–MoS_2$ composites fabricated using powder metallurgy show improved machinability and wear resistance. WEDM is effective for machining these composites with high precision. Optimization of process parameters is essential for achieving better performance. Future work can focus on advanced optimization techniques, microstructural analysis, and application-based studies for industrial implementation.

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