**Testing Aluminum Silicon Carbide to Explore Alternate Electrode Materials in the Electrical Discharge Manufacturing Process**

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**Introduction**

Electrical Discharge Manufacturing (EDM) is a non-conventional machining process where electricity is applied over a small period to a material submerged in a dielectric solution. The arc produced between the electrode and the material removes a surface layer of the material. This process is primarily used to precisely manufacture hard materials such as tungsten or steel, where traditional machining processes such as milling or grinding would be inefficient. EDM is used in the aerospace industry to reduce the surface roughness at a microscopic level, and therefore friction, of hard components found in airplane engines. Different materials are used for electrodes, with different benefits. Two common materials are copper and brass. Copper is inexpensive and resists erosion but difficult to machine. Brass is much easier to machine but wears out faster than Copper and is more expensive. Researchers are exploring Aluminum Silicon Carbide composites as an alternative to Brass and Copper as it is easier to machine than copper and less expensive than brass.

**Experimental Design**

Researchers conducted EDM experiments on pieces of 080M40 Steel submerged in dielectric oil with a specific gravity of 0.763 using four different factors: Tool material, Pulse on Time, Current, and Pulse off time (Figure 2). The primary factor of interest is the electrode tool material. The electrode tool materials were Copper, Brass, Aluminum + 3% Silicon Carbide, Aluminum + 6% Silicon Carbide and Aluminum + 9% Silicon Carbide (Figure 1). The Pulse on Time factor levels were 200, 500 and 900 microseconds. The Current factors used were 6, 8 and 10 amps. The Pulse Off Time factor levels were 100, 200 and 500 microseconds. The response the researchers measured was the surface roughness(SR) of the steel following the experiment, measured in micrometers (Figure 3). The researchers conducted 45 experiments of individual replicates based on the principles of the Taguchi design, with each tool material level containing L9 experiments(each factor level appears 3 times). This allowed the researchers to conduct 45 experiments instead of the 135 required by a full factorial design with 1 replicate. Our team analyzed the surface roughness results using ANOVA in Minitab. Each factor had discrete, rather than continuous levels so multiple linear regression was not appropriate. We decided to use forward selection (α = 0.15) and then Tukey tests to determine which factors and interactions resulted in the lowest surface roughness. For this experiment, a lower mean surface roughness (smooth finish) is considered better.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Factor Level | Tool Material | Pulse on Time(μs) | Current(A) | Pulse off Time(μs) |
| 1 | Al + 3%SiC | 200 | 6 | 100 |
| 2 | Al + 6%SiC | 500 | 8 | 200 |
| 3 | Al + 9%SiC | 900 | 10 | 500 |
| 4 | Copper | - | - | - |
| 5 | Brass | - | - | - |

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**Results**

See Appendix 1 for data results.

WORKSHEET 1

**General Linear Model: SR versus Tool, Pulse on time, Current, Pulse off time**

**Method**

|  |  |
| --- | --- |
| Factor coding | (-1, 0, +1) |

**Forward Selection of Terms**

α to enter = 0.15

**Factor Information**

|  |  |  |  |
| --- | --- | --- | --- |
| **Factor** | **Type** | **Levels** | **Values** |
| Tool | Fixed | 5 | Al6061 + 3 % SiC, Al6061 + 6% SiC, Al6061 + 9% SiC, Brass, Copper |
| Pulse on time | Fixed | 3 | 200, 500, 900 |
| Current | Fixed | 3 | 6, 8, 10 |

**Analysis of Variance**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
| Tool | 4 | 126.431 | 31.6077 | 51.23 | 0.000 |
| Pulse on time | 2 | 36.727 | 18.3634 | 29.76 | 0.000 |
| Current | 2 | 12.428 | 6.2142 | 10.07 | 0.001 |
| Tool\*Pulse on time | 8 | 11.959 | 1.4949 | 2.42 | 0.063 |
| Tool\*Current | 8 | 9.757 | 1.2196 | 1.98 | 0.117 |
| Pulse on time\*Current | 4 | 7.419 | 1.8547 | 3.01 | 0.050 |
| Error | 16 | 9.871 | 0.6170 |  |  |
| Total | 44 | 214.592 |  |  |  |

From these results, we see that Pulse Off Time did not have a significant effect on surface roughness at all. From the remaining factors, Tool Material, Pulse On Time, and Current were very significant at the 95% confidence level with p-values well below α = 0.05 and close to 0. The interaction between Pulse On Time and Current is almost significant with a p-value of 0.050, but we excluded it because p is not less than 0.05.

**Model Summary**

|  |  |  |  |
| --- | --- | --- | --- |
| **S** | **R-sq** | **R-sq(adj)** | **R-sq(pred)** |
| 0.785473 | 95.40% | 87.35% | 63.61% |

The results indicate that 87.35% of the surface roughness of the steel can be attributed to the factors.

**Coefficients**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Term** | **Coef** | **SE Coef** | **T-Value** | **P-Value** | **VIF** |
| Constant | 6.599 | 0.117 | 56.35 | 0.000 |  |
| Tool |  |  |  |  |  |
| Al6061 + 3 % SiC | 2.034 | 0.234 | 8.69 | 0.000 | 1.60 |
| Al6061 + 6% SiC | -2.247 | 0.234 | -9.59 | 0.000 | 1.60 |
| Al6061 + 9% SiC | 0.640 | 0.234 | 2.73 | 0.015 | 1.60 |
| Brass | -1.690 | 0.234 | -7.22 | 0.000 | 1.60 |
| Pulse on time |  |  |  |  |  |
| 200 | -1.190 | 0.166 | -7.18 | 0.000 | 1.33 |
| 500 | 0.191 | 0.166 | 1.16 | 0.265 | 1.33 |
| Current |  |  |  |  |  |
| 6 | -0.423 | 0.166 | -2.56 | 0.021 | 1.33 |
| 8 | -0.317 | 0.166 | -1.92 | 0.073 | 1.33 |
| Tool\*Pulse on time |  |  |  |  |  |
| Al6061 + 3 % SiC  200 | -0.389 | 0.331 | -1.17 | 0.258 | 2.13 |
| Al6061 + 3 % SiC  500 | -0.282 | 0.331 | -0.85 | 0.408 | 2.13 |
| Al6061 + 6% SiC  200 | 0.200 | 0.331 | 0.60 | 0.554 | 2.13 |
| Al6061 + 6% SiC  500 | -0.773 | 0.331 | -2.34 | 0.033 | 2.13 |
| Al6061 + 9% SiC  200 | -0.277 | 0.331 | -0.84 | 0.416 | 2.13 |
| Al6061 + 9% SiC  500 | 0.543 | 0.331 | 1.64 | 0.121 | 2.13 |
| Brass  200 | -0.022 | 0.331 | -0.07 | 0.947 | 2.13 |
| Brass  500 | -0.113 | 0.331 | -0.34 | 0.737 | 2.13 |
| Tool\*Current |  |  |  |  |  |
| Al6061 + 3 % SiC  6 | -0.212 | 0.331 | -0.64 | 0.531 | 2.13 |
| Al6061 + 3 % SiC  8 | 0.774 | 0.331 | 2.34 | 0.033 | 2.13 |
| Al6061 + 6% SiC  6 | 0.100 | 0.331 | 0.30 | 0.766 | 2.13 |
| Al6061 + 6% SiC  8 | -0.023 | 0.331 | -0.07 | 0.945 | 2.13 |
| Al6061 + 9% SiC  6 | -0.118 | 0.331 | -0.36 | 0.727 | 2.13 |
| Al6061 + 9% SiC  8 | 0.202 | 0.331 | 0.61 | 0.551 | 2.13 |
| Brass  6 | 0.803 | 0.331 | 2.42 | 0.028 | 2.13 |
| Brass  8 | -0.705 | 0.331 | -2.13 | 0.049 | 2.13 |
| Pulse on time\*Current |  |  |  |  |  |
| 200 6 | -0.005 | 0.234 | -0.02 | 0.985 | 1.78 |
| 200 8 | 0.524 | 0.234 | 2.24 | 0.040 | 1.78 |
| 500 6 | 0.405 | 0.234 | 1.73 | 0.103 | 1.78 |
| 500 8 | -0.251 | 0.234 | -1.07 | 0.299 | 1.78 |

The VIF for each term in the regression equation is less than 4, so we do not need to conduct additional investigations.

**Regression Equation**

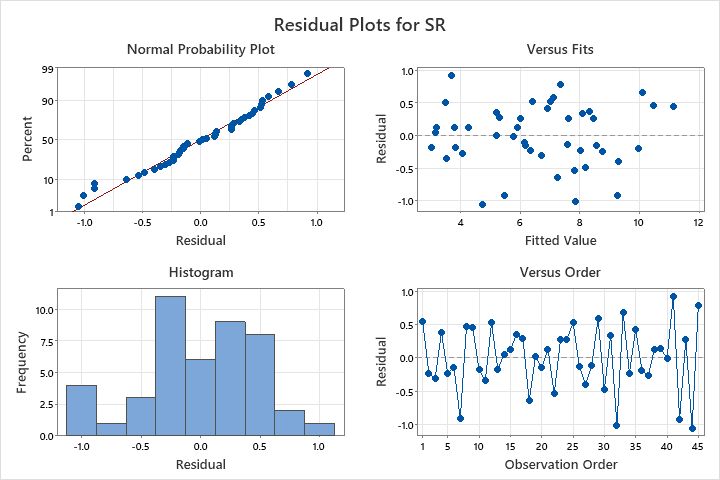
|  |  |  |
| --- | --- | --- |
| SR | = | 6.599 + 2.034 Tool\_Al6061 + 3 % SiC  - 2.247 Tool\_Al6061 + 6% SiC  + 0.640 Tool\_Al6061 + 9% SiC  - 1.690 Tool\_Brass  + 1.263 Tool\_Copper  - 1.190 Pulse on time\_200 + 0.191 Pulse on time\_500 + 0.998 Pulse on time\_900 - 0.423 Current\_6 - 0.317 Current\_8 + 0.741 Current\_10 - 0.389 Tool\*Pulse on time\_Al6061 + 3 % SiC  200 - 0.282 Tool\*Pulse on time\_Al6061 + 3 % SiC  500 + 0.670 Tool\*Pulse on time\_Al6061 + 3 % SiC  900 + 0.200 Tool\*Pulse on time\_Al6061 + 6% SiC  200 - 0.773 Tool\*Pulse on time\_Al6061 + 6% SiC  500 + 0.573 Tool\*Pulse on time\_Al6061 + 6% SiC  900 - 0.277 Tool\*Pulse on time\_Al6061 + 9% SiC  200 + 0.543 Tool\*Pulse on time\_Al6061 + 9% SiC  500 - 0.266 Tool\*Pulse on time\_Al6061 + 9% SiC  900 - 0.022 Tool\*Pulse on time\_Brass  200 - 0.113 Tool\*Pulse on time\_Brass  500 + 0.135 Tool\*Pulse on time\_Brass  900 + 0.487 Tool\*Pulse on time\_Copper  200 + 0.625 Tool\*Pulse on time\_Copper  500 - 1.113 Tool\*Pulse on time\_Copper  900 - 0.212 Tool\*Current\_Al6061 + 3 % SiC  6 + 0.774 Tool\*Current\_Al6061 + 3 % SiC  8 - 0.561 Tool\*Current\_Al6061 + 3 % SiC  10 + 0.100 Tool\*Current\_Al6061 + 6% SiC  6 - 0.023 Tool\*Current\_Al6061 + 6% SiC  8 - 0.077 Tool\*Current\_Al6061 + 6% SiC  10 - 0.118 Tool\*Current\_Al6061 + 9% SiC  6 + 0.202 Tool\*Current\_Al6061 + 9% SiC  8 - 0.084 Tool\*Current\_Al6061 + 9% SiC  10 + 0.803 Tool\*Current\_Brass  6 - 0.705 Tool\*Current\_Brass  8 - 0.098 Tool\*Current\_Brass  10 - 0.573 Tool\*Current\_Copper  6 - 0.248 Tool\*Current\_Copper  8 + 0.821 Tool\*Current\_Copper  10 - 0.005 Pulse on time\*Current\_200 6 + 0.524 Pulse on time\*Current\_200 8 - 0.519 Pulse on time\*Current\_200 10 + 0.405 Pulse on time\*Current\_500 6 - 0.251 Pulse on time\*Current\_500 8 - 0.154 Pulse on time\*Current\_500 10 - 0.401 Pulse on time\*Current\_900 6 - 0.273 Pulse on time\*Current\_900 8 + 0.673 Pulse on time\*Current\_900 10 |

**Fits and Diagnostics for Unusual Observations**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Obs** | **SR** | **Fit** | **Resid** | **Std Resid** |  |
| 32 | 6.854 | 7.862 | -1.008 | -2.15 | R |
| 44 | 3.700 | 4.747 | -1.047 | -2.24 | R |

*R  Large residual*

Here we see the 32nd and 44th observation to have a standardized residual less than -2, which means that these data points can be considered outliers.



The 4-in-1 residual plot comparison shows that ANOVA is a good method to use in the analysis. The Normal probability plot shows the relationship between the residuals follows a linear pattern. The Residual histogram shows the residuals are normally distributed. The Versus Fits plot has an even spread of points above and below zero, showing the residuals are random. The Versus Order plot has no discernible pattern, showing the residuals are independent of each other.

WORKSHEET 1

**Comparisons for SR**

**Tukey Pairwise Comparisons: Tool**

**Grouping Information Using the Tukey Method and 95% Confidence**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Tool** | **N** | **Mean** | **Grouping** | | |
| Al6061 + 3 % SiC | 9 | 8.63267 | A |  |  |
| Copper | 9 | 7.86156 | A | B |  |
| Al6061 + 9% SiC | 9 | 7.23867 |  | B |  |
| Brass | 9 | 4.90833 |  |  | C |
| Al6061 + 6% SiC | 9 | 4.35167 |  |  | C |

*Means that do not share a letter are significantly different.*

**Tukey Pairwise Comparisons: Pulse on time**

**Grouping Information Using the Tukey Method and 95% Confidence**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Pulse on time** | **N** | **Mean** | **Grouping** | | |
| 900 | 15 | 7.59687 | A |  |  |
| 500 | 15 | 6.78993 |  | B |  |
| 200 | 15 | 5.40893 |  |  | C |

*Means that do not share a letter are significantly different.*

**Tukey Pairwise Comparisons: Current**

**Grouping Information Using the Tukey Method and 95% Confidence**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Current** | **N** | **Mean** | **Grouping** | |
| 10 | 15 | 7.33927 | A |  |
| 8 | 15 | 6.28127 |  | B |
| 6 | 15 | 6.17520 |  | B |

*Means that do not share a letter are significantly different.*

Based on the Tukey Tests conducted at 95% confidence on the significant factors, we find that Brass and Aluminum with 6% Silicon Carbide resulted in the lowest mean surface roughness at 4.90833 and 4.35167 micrometers, respectively. A Pulse On Time of 200 microseconds resulted in the lowest surface roughness with a mean of 5.40893 micrometers. For current, 6 and 8 amps both resulted in the lowest surface roughness with 6.28127 and 6.17520 micrometers, respectively.

Chart, line chart

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These results are also reflected in the Main Effects Plot which show that 200 microsecond Pulse On Time, 6 and 8 amps Current and Brass and Aluminum with 6% Silicon Carbide Tool Material result in the lowest mean surface roughness.

WORKSHEET 1

**Prediction for SR**

**General Linear Model Information**

|  |
| --- |
| **Terms** |
| Tool Pulse on time Current |

**Settings**

|  |  |
| --- | --- |
| **Variable** | **Setting** |
| Tool | Al6061 + 6% SiC |
| Pulse on time | 200 |
| Current | 6 |

**Prediction**

|  |  |  |  |
| --- | --- | --- | --- |
| **Fit** | **SE Fit** | **95% CI** | **95% PI** |
| 2.73864 | 0.465510 | (1.79455, 3.68274) | (0.426085, 5.05120) |

**Settings**

|  |  |
| --- | --- |
| **Variable** | **Setting** |
| Tool | Al6061 + 6% SiC |
| Pulse on time | 200 |
| Current | 8 |

**Prediction**

|  |  |  |  |
| --- | --- | --- | --- |
| **Fit** | **SE Fit** | **95% CI** | **95% PI** |
| 2.84471 | 0.465510 | (1.90061, 3.78881) | (0.532151, 5.15727) |

**Settings**

|  |  |
| --- | --- |
| **Variable** | **Setting** |
| Tool | Brass |
| Pulse on time | 200 |
| Current | 6 |

**Prediction**

|  |  |  |  |
| --- | --- | --- | --- |
| **Fit** | **SE Fit** | **95% CI** | **95% PI** |
| 3.29531 | 0.465510 | (2.35121, 4.23941) | (0.982751, 5.60787) |

**Settings**

|  |  |
| --- | --- |
| **Variable** | **Setting** |
| Tool | Brass |
| Pulse on time | 200 |
| Current | 8 |

**Prediction**

|  |  |  |  |
| --- | --- | --- | --- |
| **Fit** | **SE Fit** | **95% CI** | **95% PI** |
| 3.40138 | 0.465510 | (2.45728, 4.34548) | (1.08882, 5.71394) |

Conducting a response prediction in Minitab based on the significant factor levels, we found the following.

Mean SR (Al + 6% SiC, 200μs, 6A) = 2.73864 μm, 95% CI (1.79455, 3.68274)

Mean SR (Al + 6% SiC, 200μs, 8A) = 2.84471 μm, 95% CI (1.90061, 3.78881)

Mean SR (Brass, 200μs, 6A) = 3.29531 μm, 95% CI (2.35121, 4.23941)

Mean SR (Brass, 200μs, 8A) = 3.40138 μm, 95% CI (2.45728, 4.34548)

**Conclusion**

We conclude that electrodes made of Aluminum + 6% Silicon Carbide and Brass result in the lowest surface roughness. We also found that currents of 6 and 8 Amps, and a Pulse on Time of 200 μs resulted in the lowest surface roughness. We believe that constructing electrodes made from a composite material of Aluminum + 6% Silicon Carbide is a suitable replacement for Brass in the Electrical Discharge Manufacturing process.

**References**

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**Appendix 1: Run order and Response Data**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Tool | Pulse on time | Current | Pulse off time | SR |
| Al6061 + 3 % SiC | 200 | 6 | 100 | 6.947 |
| Al6061 + 3 % SiC | 200 | 8 | 200 | 7.805 |
| Al6061 + 3 % SiC | 200 | 10 | 500 | 6.411 |
| Al6061 + 3 % SiC | 500 | 6 | 500 | 8.69 |
| Al6061 + 3 % SiC | 500 | 8 | 100 | 8.512 |
| Al6061 + 3 % SiC | 500 | 10 | 200 | 8.425 |
| Al6061 + 3 % SiC | 900 | 6 | 200 | 8.354 |
| Al6061 + 3 % SiC | 900 | 8 | 500 | 10.95 |
| Al6061 + 3 % SiC | 900 | 10 | 100 | 11.6 |
| Al6061 + 6% SiC | 200 | 6 | 100 | 2.859 |
| Al6061 + 6% SiC | 200 | 8 | 200 | 3.203 |
| Al6061 + 6% SiC | 200 | 10 | 500 | 4.025 |
| Al6061 + 6% SiC | 500 | 6 | 500 | 3.675 |
| Al6061 + 6% SiC | 500 | 8 | 100 | 3.234 |
| Al6061 + 6% SiC | 500 | 10 | 200 | 4.4 |
| Al6061 + 6% SiC | 900 | 6 | 200 | 5.551 |
| Al6061 + 6% SiC | 900 | 8 | 500 | 5.597 |
| Al6061 + 6% SiC | 900 | 10 | 100 | 6.621 |
| Al6061 + 9% SiC | 200 | 6 | 100 | 5.24 |
| Al6061 + 9% SiC | 200 | 8 | 200 | 6.038 |
| Al6061 + 9% SiC | 200 | 10 | 500 | 6.039 |
| Al6061 + 9% SiC | 500 | 6 | 500 | 7.303 |
| Al6061 + 9% SiC | 500 | 8 | 100 | 7.874 |
| Al6061 + 9% SiC | 500 | 10 | 200 | 8.742 |
| Al6061 + 9% SiC | 900 | 6 | 200 | 7.55 |
| Al6061 + 9% SiC | 900 | 8 | 500 | 7.458 |
| Al6061 + 9% SiC | 900 | 10 | 100 | 8.904 |
| Copper | 200 | 6 | 100 | 6.05 |
| Copper | 200 | 8 | 200 | 7.705 |
| Copper | 200 | 10 | 500 | 7.723 |
| Copper | 500 | 6 | 500 | 8.426 |
| Copper | 500 | 8 | 100 | 6.854 |
| Copper | 500 | 10 | 200 | 10.754 |
| Copper | 900 | 6 | 200 | 6.119 |
| Copper | 900 | 8 | 500 | 7.33 |
| Copper | 900 | 10 | 100 | 9.793 |
| Brass | 200 | 6 | 100 | 3.809 |
| Brass | 200 | 8 | 200 | 3.326 |
| Brass | 200 | 10 | 500 | 3.954 |
| Brass | 500 | 6 | 500 | 5.766 |
| Brass | 500 | 8 | 100 | 4.633 |
| Brass | 500 | 10 | 200 | 4.561 |
| Brass | 900 | 6 | 200 | 6.289 |
| Brass | 900 | 8 | 500 | 3.7 |
| Brass | 900 | 10 | 100 | 8.137 |