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# Process parameter optimization of abrasive water jet machining on monel k400 alloy

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**Abstract:** Nowadays it's difficult to use a metal with high corrosion resistant properties in required applications. Monel 400 is one nickel based alloy having required property to be applicable in such scenarios. It is used in highly corrosive environments such as marine, chemical and aerospace industries as it has the property of maintaining its toughness over a range of temperature, however machining of this Monel alloy is relatively tough due to its characteristic work hardening properties. To tackle the mentioned issues, Abrasive water jet machining is used which is a widely known nontraditional machining technique. The process parameters and the response variables were chosen depending on the machine specifications, and parameter combinations were made using Minitab statistical software. The parameters and their interactions like the cut quality on the alloy, nozzle diameters effects, and water pressure were also studied. Response surface model and various statistical algorithms such as S-N ratio, ANOVA and regression equations were utilized for formation of the design of experiment, optimization of process parameters for the machining process were done using Grey relations. Reduction of surface roughness, maximization of Material removal rate while simultaneously reducing the cycle time for the operation was the primary objective. The results thus obtained indicates that the quality of cut was the most influential factor in the machining process followed by water-jet pressure value.

## 1. Introduction

Abrasive water-jet machining is a blasting machining process which uses abrasives driven by a high velocity water-jet to wear away material from the work piece. Common applications include cutting heat-sensitive, brittle, thin, or hard materials. Precisely it is used to cut intricate shapes or form specific edge shapes. Material is removed by fine abrasive particles, usually about 0.001 in (0.025 mm) in diameter driven by a high velocity water jet stream. Pressures of the water jet ranges from 25000 to 60000 psi. AWJM machines are usually self-contained cantilever or gantry type machines. First the water pressure is increased and then is mixed with the abrasive in a mixing chamber which then exits through a convergent nozzle. Nozzles must be highly resistant to abrasion and thus are typically made of tungsten carbide or synthetic sapphire.

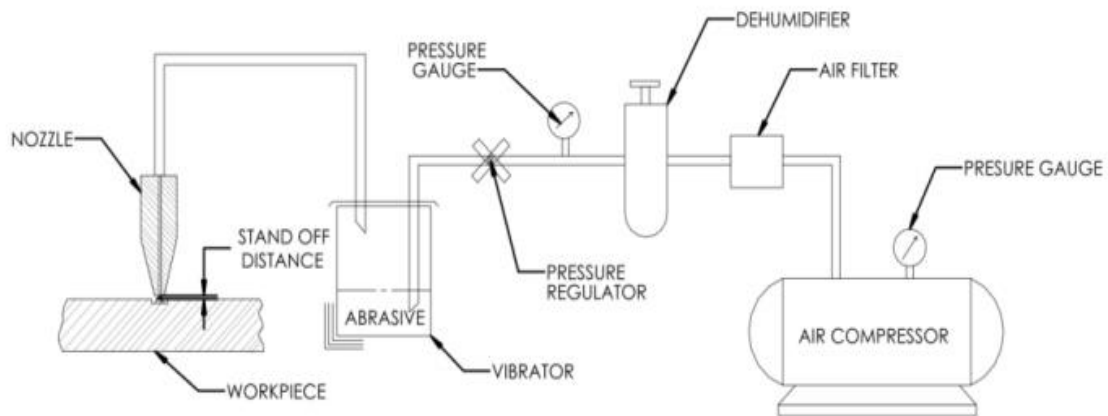
The varying effects of water pressure, Abrasive flow rate, Orifice diameter, focusing nozzle diameter, Stand-off distance on Material removal rate & surface roughness for Copper Iron alloy [1]. Characterization of AWJ process on the production of pockets in Inconel 718 established relations between critical process parameters which concluded that with increase in mass flow rate of abrasive the depth of cut value increased [2]. The effects of process parameter in Abrasive water jet machining were investigated using Response Surface Methodology which observed that pressure and transverse



rate has much effect on surface roughness than standoff distance [3]. Based on research papers, experience, Minitab software readings & available AWJ machine specifications, input & output parameters were chosen & machining was performed on Monel k400.

## 2. Materials and methods

All the samples of Monel K400 alloy has a composition of 64.27% Nickel, 32.337% Copper, 0.0269% Carbon, 0.748% Manganese, 0.19% Silicon and less than 0.0017% Sulphur. The alloy has a density of  $8.8 \times 10^3 \text{ Kg/m}^3$ , modulus of elasticity of 179 Gpa, Tensile strength of 550 MPa and hardness number 42 HRC.



**Figure 1.** Setup of abrasive water jet machining.



**Figure 2.** Machined work piece.

The Monel K400 work piece of dimensions  $410 \times 250 \times 5$  is mounted using an Abrasive Water Jet Machine (OMAX MAXIEM 1515) that uses the garnet almanide as an abrasive (60-200 mesh), 31 holes with 10mm diameter and 31 square slots with 20mm side length are cut into the work piece. Each slot and hole is machined by varying the input parameters of the AWJM set-up. The primary objective is to increase the efficiency of the process of AWJM, this includes achieving highest material removal rate, least surface roughness of the cut, achieving optimal stand-off distance, better surface finish with lower process time and achieving minimum circularity value. SURFCOM is used to

measure the surface roughness of the machined entity with high accuracy upto 0.31nm. For testing the circularity of the machined slots, Machine Vision setup (Optiv Lite OLM 3020) is used.

Design of Experiments methodology is used to determine the relationship between the input and output (cause and effect relationship) of the process. Controllable and uncontrollable input factors and responses are used in our experiment. Controllable input factors include Pressure, Stand-off distance, Quality of cut, Nozzle diameter, those of uncontrolled include unpredictable parameters such as the ambient temperature and the responses or output measures include material removal rate, surface roughness and circularity. The selection of the appropriate model for the experiments is highly imperative as it will be a deciding factor for the number of test cases that would be produced. The central composite approach was chosen as it shown to have fewer number of test cases as compared to the Box-Behnken model. For our parameter and response values we got 31 as our test case number from the central composite model. The range of the input parameters was decided and the values were entered in to the software dialog box, from wherein the software converts this given range into the test grouped combinations in a specific sequence, according to which the machining process was carried out. Response Surface Methodology is used to explore the relationships between several explanatory variables & one or more response variables. The main idea of this method is to use sequence of designed experiments to obtain an optimal response.

### 3. Results and observations

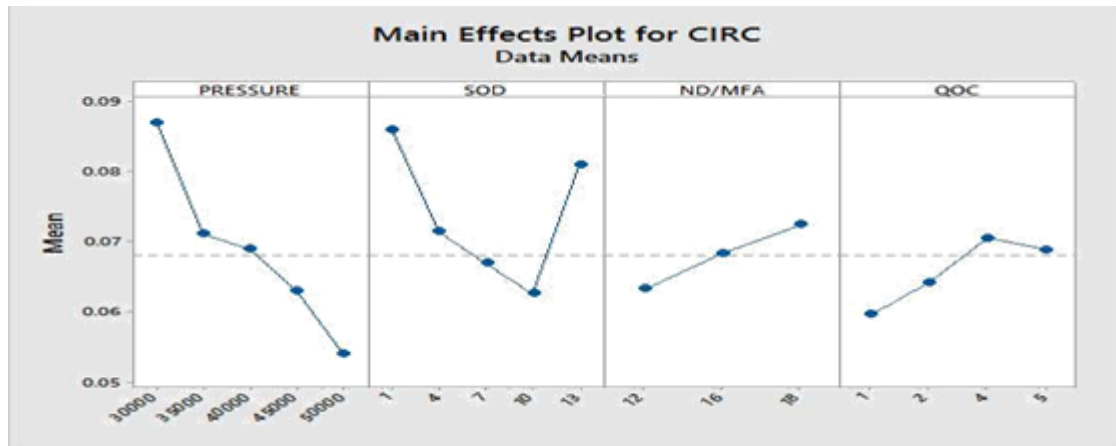
#### 3.1 Output response variables.

The measurement and calculations of circularity, material removal rate and surface roughness values for the varying ranges of pressure, stand-off distance, quality of cut, nozzle diameter are tabulated in the table 1 and Main effects plot for circularity and MRR is explained in figure 3 and 4 .

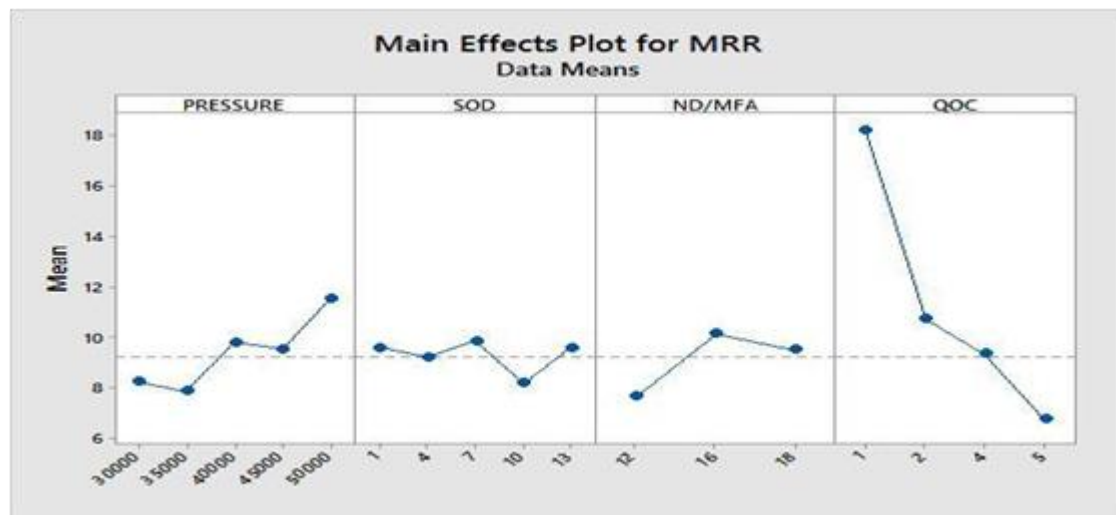
**Table 1.** Response variable table.

| <b>M<br/>O</b> | <b>SR</b> | <b>PRESSURE</b> | <b>SOD</b> | <b>ND</b> | <b>QOC</b> | <b>SURF<br/>RGHNS</b> | <b>MRR</b> | <b>CIRCULARIT<br/>Y</b> |
|----------------|-----------|-----------------|------------|-----------|------------|-----------------------|------------|-------------------------|
| 1              | 11        | 40000           | 7          | 16        | 1          | 2.4435                | 18.21053   | 0.089                   |
| 2              | 23        | 37500           | 4          | 14        | 5          | 1.7005                | 5.864407   | 0.083                   |
| 3              | 27        | 40000           | 7          | 14        | 4          | 2.2424                | 8.238095   | 0.074                   |
| 4              | 10        | 36000           | 7          | 16        | 4          | 1.9515                | 8.238095   | 0.087                   |
| 5              | 5         | 40000           | 7          | 12        | 4          | 1.9803                | 7.061224   | 0.088                   |
| 6              | 24        | 37500           | 4          | 14        | 2          | 2.2247                | 11.16129   | 0.081                   |
| 7              | 12        | 40000           | 1          | 16        | 4          | 1.8523                | 9.611111   | 0.086                   |
| 8              | 13        | 40000           | 7          | 16        | 4          | 2.0256                | 9.611111   | 0.068                   |
| 9              | 25        | 37500           | 10         | 14        | 5          | 3.2442                | 11.16129   | 0.094                   |
| 10             | 6         | 45000           | 10         | 12        | 5          | 1.8458                | 6.92       | 0.083                   |
| 11             | 14        | 40000           | 7          | 16        | 4          | 2.6458                | 9.611111   | 0.075                   |
| 12             | 15        | 40000           | 7          | 16        | 4          | 3.3709                | 9.611111   | 0.065                   |
| 13             | 16        | 40000           | 7          | 16        | 4          | 3.245                 | 9.611111   | 0.062                   |
| 14             | 1         | 37500           | 4          | 12        | 5          | 1.7791                | 4.271605   | 0.09                    |
| 15             | 17        | 40000           | 7          | 16        | 5          | 1.8853                | 7.521739   | 0.061                   |
| 16             | 22        | 45000           | 7          | 16        | 4          | 2.1058                | 11.53333   | 0.054                   |
| 17             | 18        | 40000           | 7          | 16        | 4          | 1.9211                | 9.611111   | 0.055                   |
| 18             | 2         | 37500           | 4          | 12        | 2          | 1.9099                | 9.351351   | 0.08                    |
| 19             | 3         | 37500           | 10         | 12        | 2          | 1.6089                | 9.351351   | 0.118                   |
| 20             | 19        | 40000           | 7          | 16        | 4          | 2.0301                | 9.611111   | 0.09                    |
| 21             | 7         | 45000           | 4          | 12        | 5          | 2.4861                | 6.92       | 0.11                    |
| 22             | 28        | 45000           | 4          | 14        | 2          | 3.5475                | 15.04348   | 0.087                   |
| 23             | 8         | 45000           | 10         | 12        | 2          | 2.8702                | 6.92       | 0.083                   |

|    |    |       |    |    |   |        |          |       |
|----|----|-------|----|----|---|--------|----------|-------|
| 24 | 29 | 45000 | 10 | 14 | 2 | 2.8669 | 15.04348 | 0.095 |
| 25 | 4  | 37500 | 10 | 12 | 5 | 1.8121 | 4.805556 | 0.093 |
| 26 | 26 | 37500 | 10 | 14 | 2 | 2.1945 | 5.864407 | 0.08  |
| 27 | 20 | 40000 | 10 | 16 | 4 | 2.3431 | 9.611111 | 0.092 |
| 28 | 30 | 45000 | 4  | 14 | 5 | 1.9047 | 7.863636 | 0.07  |
| 29 | 31 | 45000 | 10 | 14 | 5 | 2.6346 | 7.863636 | 0.102 |
| 30 | 9  | 45000 | 4  | 12 | 2 | 2.2714 | 13.30769 | 0.092 |
| 31 | 21 | 40000 | 7  | 16 | 4 | 1.3913 | 9.611111 | 0.1   |



**Figure 3.** Main effects plot for circularity.



**Figure 4.** Main effects plot for material removal rate.

### 3.2 Signal to noise ratio values.

The signal-to-noise ratio measures how the response signal varies with respect to the target value under varying noise conditions. One can choose from different signal-to-noise ratios, depending on the goal of our experiment. In our experiment we have used the goal of maximizing the response of MRR, as more is the MRR value, the machining process will be much faster, and as a result the cycle time will be less. At the same time we have the goal of minimizing the response of Surface Roughness and Circularity values, so as to obtain a smoother finish and distinct, defined machined surface. The

following table consists of the tabulations of the obtained S/N ratios for each our response variables. These S/N ratio are used to calculate the normalized S/N ratio's and also used to formulate the Grey coefficient and the Grey grade as in table 2

**Table 2.** S/N Ratio for Response Variables.

| MO | SR | P     | S  | N  | Q | S/N SR   | S/N MRR  | S/N CIRC |
|----|----|-------|----|----|---|----------|----------|----------|
| 1  | 11 | 40000 | 7  | 16 | 1 | -7.76025 | 25.20645 | 21.0122  |
| 2  | 23 | 37500 | 4  | 14 | 5 | -4.61153 | 15.36448 | 21.61844 |
| 3  | 27 | 40000 | 7  | 14 | 4 | -7.01426 | 18.31654 | 22.61537 |
| 4  | 10 | 36000 | 7  | 16 | 4 | -5.80737 | 18.31654 | 21.20961 |
| 5  | 5  | 40000 | 7  | 12 | 4 | -5.93462 | 16.9776  | 21.11035 |
| 6  | 24 | 37500 | 4  | 14 | 2 | -6.94543 | 20.95429 | 21.8303  |
| 7  | 12 | 40000 | 1  | 16 | 4 | -5.35423 | 19.65547 | 21.31003 |
| 8  | 13 | 40000 | 7  | 16 | 4 | -6.13107 | 19.65547 | 23.34982 |
| 9  | 25 | 37500 | 10 | 14 | 5 | -10.2222 | 20.95429 | 20.53744 |
| 10 | 6  | 45000 | 10 | 12 | 5 | -5.32369 | 16.80212 | 21.61844 |
| 11 | 14 | 40000 | 7  | 16 | 4 | -8.45114 | 19.65547 | 22.49877 |
| 12 | 15 | 40000 | 7  | 16 | 4 | -10.5549 | 19.65547 | 23.74173 |
| 13 | 16 | 40000 | 7  | 16 | 4 | -10.2243 | 19.65547 | 24.15217 |
| 14 | 1  | 37500 | 4  | 12 | 5 | -5.00401 | 12.61182 | 20.91515 |
| 15 | 17 | 40000 | 7  | 16 | 5 | -5.50761 | 17.52637 | 24.2934  |
| 16 | 22 | 45000 | 7  | 16 | 4 | -6.46834 | 21.2391  | 25.35212 |
| 17 | 18 | 40000 | 7  | 16 | 4 | -5.671   | 19.65547 | 25.19275 |
| 18 | 2  | 37500 | 4  | 12 | 2 | -5.62021 | 19.41749 | 21.9382  |
| 19 | 3  | 37500 | 10 | 12 | 2 | -4.13058 | 19.41749 | 18.56236 |
| 20 | 19 | 40000 | 7  | 16 | 4 | -6.15035 | 19.65547 | 20.91515 |
| 21 | 7  | 45000 | 4  | 12 | 5 | -7.91037 | 16.80212 | 19.17215 |
| 22 | 28 | 45000 | 4  | 14 | 2 | -10.9984 | 23.54697 | 21.20961 |
| 23 | 8  | 45000 | 10 | 12 | 2 | -9.15824 | 16.80212 | 21.61844 |
| 24 | 29 | 45000 | 10 | 14 | 2 | -9.14825 | 23.54697 | 20.44553 |
| 25 | 4  | 37500 | 10 | 12 | 5 | -5.16364 | 13.63487 | 20.63034 |
| 26 | 26 | 37500 | 10 | 14 | 2 | -6.82671 | 15.36448 | 21.9382  |
| 27 | 20 | 40000 | 10 | 16 | 4 | -7.39582 | 19.65547 | 20.72424 |
| 28 | 30 | 45000 | 4  | 14 | 5 | -5.59653 | 17.91247 | 23.09804 |
| 29 | 31 | 45000 | 10 | 14 | 5 | -8.41429 | 17.91247 | 19.828   |
| 30 | 9  | 45000 | 4  | 12 | 2 | -7.12587 | 22.48206 | 20.72424 |
| 31 | 21 | 40000 | 7  | 16 | 4 | -2.86842 | 19.65547 | 20       |

### 3.3 Grey coefficient and grey relation grade.

Greys coefficient (GC) and Grey relation grade (GRG) are the formulation sets on the basis of which the multi variable response optimization is carried out so as to obtain the best fit from the varied number of test cases. The GRG value is used to then rank the reading sets in a descending order. The one set with the lowest rank, but highest GRG value is said to be the optimal set as in table 3.

**Table 3.** Values of Grey coefficients for all response variables.

| S. N O | GRG      | RANK | PRESSURE | SOD | N  | QOC | GC SR    | GC-MRR   | GC-C     |
|--------|----------|------|----------|-----|----|-----|----------|----------|----------|
| 1      | 0.444366 | 27   | 37500    | 4   | 12 | 5   | 0.52049  | 0.333333 | 0.590653 |
| 2      | 0.486755 | 19   | 37500    | 4   | 12 | 2   | 0.465972 | 0.52103  | 0.501406 |
| 3      | 0.63178  | 5    | 37500    | 10  | 12 | 2   | 0.454095 | 0.52103  | 1        |
| 4      | 0.463349 | 25   | 37500    | 10  | 12 | 5   | 0.920315 | 0.352418 | 0.621447 |
| 5      | 0.486288 | 20   | 40000    | 7   | 12 | 4   | 0.548851 | 0.433515 | 0.571253 |
| 6      | 0.459375 | 26   | 45000    | 10  | 12 | 5   | 0.507597 | 0.428341 | 0.52626  |
| 7      | 0.622818 | 6    | 45000    | 4   | 12 | 5   | 0.423523 | 0.428341 | 0.847731 |
| 8      | 0.562685 | 12   | 45000    | 10  | 12 | 2   | 0.424953 | 0.428341 | 0.52626  |
| 9      | 0.612481 | 7    | 45000    | 4   | 12 | 2   | 0.733455 | 0.698018 | 0.610946 |
| 10     | 0.495589 | 18   | 36000    | 7   | 16 | 4   | 0.440378 | 0.477531 | 0.561868 |
| 11     | 0.719943 | 2    | 40000    | 7   | 16 | 1   | 0.43783  | 1        | 0.580846 |
| 12     | 0.503044 | 17   | 40000    | 1   | 16 | 4   | 0.432285 | 0.531496 | 0.552683 |
| 13     | 0.470428 | 23   | 40000    | 7   | 16 | 4   | 0.392704 | 0.531496 | 0.414903 |
| 14     | 0.546937 | 13   | 40000    | 7   | 16 | 4   | 0.464885 | 0.531496 | 0.463067 |
| 15     | 0.642478 | 4    | 40000    | 7   | 16 | 4   | 0.592382 | 0.531496 | 0.395939 |
| 16     | 0.610045 | 9    | 40000    | 7   | 16 | 4   | 0.447368 | 0.531496 | 0.377852 |
| 17     | 0.418275 | 31   | 40000    | 7   | 16 | 5   | 0.642268 | 0.450535 | 0.372004 |
| 18     | 0.436835 | 29   | 40000    | 7   | 16 | 4   | 0.436652 | 0.531496 | 0.338633 |
| 19     | 0.529374 | 15   | 40000    | 7   | 16 | 4   | 1        | 0.531496 | 0.590653 |
| 20     | 0.563764 | 11   | 40000    | 10  | 16 | 4   | 0.578984 | 0.531496 | 0.610946 |
| 21     | 0.522445 | 16   | 40000    | 7   | 16 | 4   | 0.920787 | 0.531496 | 0.702507 |
| 22     | 0.477162 | 22   | 45000    | 7   | 16 | 4   | 0.484658 | 0.613494 | 0.333333 |
| 23     | 0.436383 | 30   | 37500    | 4   | 14 | 5   | 0.732059 | 0.390186 | 0.52626  |
| 24     | 0.540714 | 14   | 37500    | 4   | 14 | 2   | 0.646247 | 0.596931 | 0.509526 |
| 25     | 0.716482 | 3    | 37500    | 10  | 14 | 5   | 0.416183 | 0.596931 | 0.632198 |
| 26     | 0.466396 | 24   | 37500    | 10  | 14 | 2   | 0.515683 | 0.390186 | 0.501406 |
| 27     | 0.484613 | 21   | 40000    | 7   | 14 | 4   | 0.333333 | 0.477531 | 0.455818 |
| 28     | 0.571896 | 10   | 45000    | 4   | 14 | 2   | 0.409111 | 0.791438 | 0.561868 |
| 29     | 0.722235 | 1    | 45000    | 10  | 14 | 2   | 0.374309 | 0.791438 | 0.643208 |
| 30     | 0.442687 | 28   | 45000    | 4   | 14 | 5   | 0.362381 | 0.463334 | 0.428076 |
| 31     | 0.611346 | 8    | 45000    | 10  | 14 | 5   | 0.528478 | 0.463334 | 0.728434 |

The above tabulation shows the rank of the various test cases in accordance with Grey relation grade value. The higher this value the much better and optimal is the multi variable response for a given model as in table 4

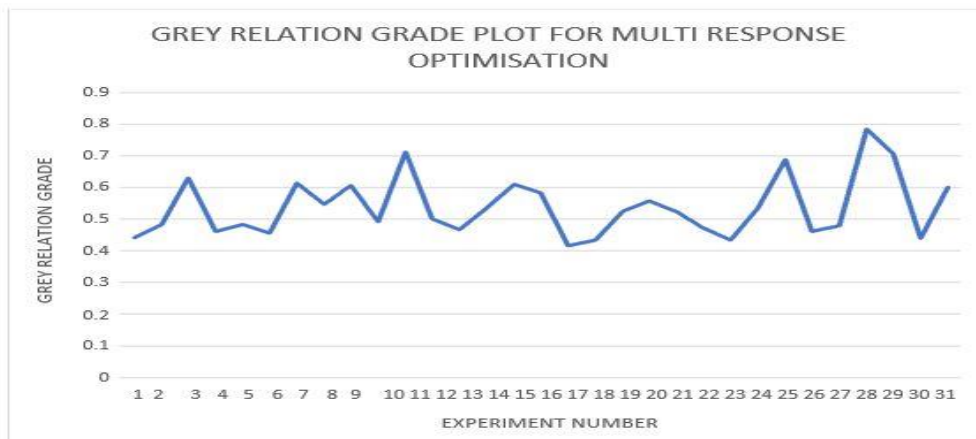
**Table 4.** Rank variables based on GRG values.

| RANK | GRG      | PRESSURE | SOD | ND | QOC |
|------|----------|----------|-----|----|-----|
| 1    | 0.722235 | 45000    | 10  | 14 | 2   |
| 2    | 0.719943 | 40000    | 7   | 16 | 1   |
| 3    | 0.716482 | 37500    | 10  | 14 | 5   |
| 4    | 0.642478 | 40000    | 7   | 16 | 4   |
| 5    | 0.63178  | 37500    | 10  | 12 | 2   |
| 6    | 0.622818 | 45000    | 4   | 12 | 5   |
| 7    | 0.612481 | 45000    | 4   | 12 | 2   |



|    |          |       |    |    |   |
|----|----------|-------|----|----|---|
| 8  | 0.611346 | 45000 | 10 | 14 | 5 |
| 9  | 0.610045 | 40000 | 7  | 16 | 4 |
| 10 | 0.571896 | 45000 | 4  | 14 | 2 |
| 11 | 0.563764 | 40000 | 10 | 16 | 4 |
| 12 | 0.562685 | 45000 | 10 | 12 | 2 |
| 13 | 0.546937 | 40000 | 7  | 16 | 4 |
| 14 | 0.540714 | 37500 | 4  | 14 | 2 |
| 15 | 0.529374 | 40000 | 7  | 16 | 4 |
| 16 | 0.522445 | 40000 | 7  | 16 | 4 |
| 17 | 0.503044 | 40000 | 1  | 16 | 4 |
| 18 | 0.495589 | 36000 | 7  | 16 | 4 |
| 19 | 0.486755 | 37500 | 4  | 12 | 2 |
| 20 | 0.486288 | 40000 | 7  | 12 | 4 |
| 21 | 0.484613 | 40000 | 7  | 14 | 4 |
| 22 | 0.477162 | 45000 | 7  | 16 | 4 |
| 23 | 0.470428 | 40000 | 7  | 16 | 4 |
| 24 | 0.466396 | 37500 | 10 | 14 | 2 |
| 25 | 0.463349 | 37500 | 10 | 12 | 5 |
| 26 | 0.459375 | 45000 | 10 | 12 | 5 |
| 27 | 0.444366 | 37500 | 4  | 12 | 5 |
| 28 | 0.442687 | 45000 | 4  | 14 | 5 |
| 29 | 0.436835 | 40000 | 7  | 16 | 4 |
| 30 | 0.436383 | 37500 | 4  | 14 | 5 |
| 31 | 0.418275 | 40000 | 7  | 16 | 5 |

Also it can be observed that the value of the first ranked test case is  $GRG = 0.784435$ .



**Figure 5.** Grey relation plot for multi-response optimization.

The below shown tabulation displays the level values that we have chosen for our project. The levels indicate the lower value, higher value, and the intermediate stage

**Table 5.** Input Factor Levels.

| INPUT FACTORS | LEVEL 1   | LEVEL 2   | LEVEL 3   |
|---------------|-----------|-----------|-----------|
| PRESSURE      | 37500 psi | 40000 psi | 45000 psi |
| SOD           | 4mm       | 7mm       | 10mm      |
| QOC           | 2         | 4         | 5         |
| ND/MFA        | 12mm      | 14mm      | 16mm      |

In order to calculate the most influencing factor in our experiment we need to find the mean grey relational grade in our experiment, for all the level, of all the parameters and variables that is list table 5 The levels of each parameter have been assigned a calculated averaged/mean Grey relation grade as in the table 6, which has been found out using the MS Excel program. Using the mean grey relation values at distinct levels we also found out that pressure would be optimal at level 3, standoff distance would be optimal at level 3, quality of cut would be optimal at level 1, and the nozzle diameter would be optimal at level 2 as the respective mean gray values are of the highest level.

**Table 6.** Mean of Grey Relation Grade.

| INPUT FACTORS | LEVEL 1   | LEVEL 2   | LEVEL 3   | DIFF = MAX-MIN |
|---------------|-----------|-----------|-----------|----------------|
| PRESSURE      | 0.5202015 | 0.5334206 | 0.5647426 | 0.044541095    |
| SOD           | 0.5179047 | 0.5261855 | 0.5774902 | 0.057288651    |
| QOC           | 0.5905427 | 0.5206924 | 0.5127866 | 0.077756101    |
| ND/MFA        | 0.5299884 | 0.5547501 | 0.5335629 | 0.024761672    |

**Table 7.** Optimum Input Parameter Level.

| PRESSURE | SOD | ND | QOC |
|----------|-----|----|-----|
| 45000    | 10  | 14 | 1   |

It is also observed that the difference between mean Gray relation value ranges is maximum for the Nozzle diameter. Hence due to which we are able to conclude that the Nozzle diameter is the most influencing parameter in our machining process.

### 3.4 ANOVA – Analysis of variance.

Analysis of variance (ANOVA) tests the hypothesis whether the two or more populations are equal. The importance of one or more factors by comparing the response variable means at the different factor levels can be determined by ANNOVA. The most important statistic in the analysis of variance table is the p-value (P). The p-value for a term asserts the significance of it. If P is less than or equal to the a-level (0.005), then the effect for the term is significant. If P is larger than the a-level, then the effect is not significant.

### 3.4.1 Response Surface Regression for Surface Roughness.

**Table 8.** Analysis of Variance for SR.

| Source            | DF | Adj SS  | Adj MS   | F-Value | P-Value |
|-------------------|----|---------|----------|---------|---------|
| Model             | 14 | 1.93678 | 0.138341 | 4.39    | 0.003   |
| Linear            | 4  | 0.52957 | 0.132393 | 4.21    | 0.016   |
| PRESSURE          | 1  | 0.22733 | 0.227332 | 7.22    | 0.016   |
| SOD               | 1  | 0.03563 | 0.035628 | 1.13    | 0.303   |
| ND/MFA            | 1  | 0.04447 | 0.044474 | 1.41    | 0.252   |
| QOC               | 1  | 0.22187 | 0.221875 | 7.05    | 0.017   |
| Square            | 4  | 0.12180 | 0.030450 | 0.97    | 0.452   |
| PRESSURE*PRESSURE | 1  | 0.01493 | 0.014927 | 0.47    | 0.501   |
| SOD*SOD           | 1  | 0.08996 | 0.089964 | 2.86    | 0.110   |
| ND/MFA*ND/MFA     | 1  | 0.00041 | 0.000407 | 0.01    | 0.911   |
| QOC*QOC           | 1  | 0.01885 | 0.018849 | 0.60    | 0.450   |
| 2-Way Interaction | 6  | 1.09060 | 0.181767 | 5.77    | 0.002   |
| PRESSURE*SOD      | 1  | 0.22300 | 0.222996 | 7.08    | 0.017   |
| PRESSURE*ND/MFA   | 1  | 0.07273 | 0.072732 | 2.31    | 0.148   |
| PRESSURE*QOC      | 1  | 0.02388 | 0.023882 | 0.76    | 0.397   |
| SOD*ND/MFA        | 1  | 0.65685 | 0.656851 | 20.86   | 0.000   |
| SOD*QOC           | 1  | 0.01224 | 0.012242 | 0.39    | 0.542   |
| ND/MFA*QOC        | 1  | 0.09749 | 0.097486 | 3.10    | 0.098   |

Regression equation for SR in uncoded units –

$$\begin{aligned}
 &1.93 + 0.000050 \text{ PRESSURE} - 0.113 \text{ SOD} - 0.087 \text{ ND/MFA} - 0.266 \text{ QOC} \\
 &+ 0.000000 \text{ PRESSURE*PRESSURE} + 0.00625 \text{ SOD*SOD} \\
 &+ 0.00107 \text{ ND/MFA*ND/MFA} - 0.0230 \text{ QOC*QOC} - 0.000008 \text{ PRESSURE*SOD} - \\
 &0.000004 \text{ PRESSURE*ND/MFA} \\
 &+ 0.000005 \text{ PRESSURE*QOC} + 0.02212 \text{ SOD*ND/MFA} + 0.00604 \text{ SOD*QOC} \\
 &+ 0.01713 \text{ ND/MFA*QOC}
 \end{aligned}$$

### 3.4.2 Response Surface Regression for MRR.

**Table 9.** Analysis of Variance for MRR.

| Source            | DF | Adj SS  | Adj MS  | F-Value | P-Value |
|-------------------|----|---------|---------|---------|---------|
| Model             | 14 | 216.773 | 15.4838 | 16.45   | 0.000   |
| Linear            | 4  | 122.670 | 30.6675 | 32.59   | 0.000   |
| PRESSURE          | 1  | 16.506  | 16.5059 | 17.54   | 0.001   |
| SOD               | 1  | 5.265   | 05.2647 | 05.59   | 0.031   |
| ND/MFA            | 1  | 15.834  | 15.8338 | 16.82   | 0.001   |
| QOC               | 1  | 84.969  | 84.9686 | 90.28   | 0.000   |
| Square            | 4  | 31.657  | 7.9142  | 8.41    | 0.001   |
| PRESSURE*PRESSURE | 1  | 0.026   | 0.0256  | 0.03    | 0.871   |
| SOD*SOD           | 1  | 0.043   | 0.0425  | 0.05    | 0.834   |
| ND/MFA*ND/MFA     | 1  | 29.410  | 29.4104 | 31.25   | 0.000   |
| QOC*QOC           | 1  | 9.932   | 9.9320  | 10.55   | 0.005   |
| 2-Way Interaction | 6  | 25.599  | 4.2665  | 4.53    | 0.007   |
| PRESSURE*SOD      | 1  | 8.269   | 8.2691  | 8.79    | 0.009   |
| PRESSURE*ND/MFA   | 1  | 0.053   | 0.0528  | 0.06    | 0.816   |

|              |    |         |         |         |       |
|--------------|----|---------|---------|---------|-------|
| PRESSURE*QOC | 1  | 0.259   | 0.2594  | 0.28    | 0.607 |
| SOD*ND/MFA   | 1  | 0.878   | 0.8780  | 0.93    | 0.348 |
| SOD*QOC      | 1  | 15.669  | 15.6692 | 16.65   | 0.001 |
| ND/MFA*QOC   | 1  | 0.192   | 0.1920  | 0.20    | 0.658 |
| Error        | 16 | 15.058  | 0.9411  |         |       |
| Lack-of-Fit  | 10 | 15.058  | 1.5058  | 1.65242 | 0.000 |
| Pure Error   | 6  | 0.000   | 0.0000  |         |       |
| Total        | 30 | 231.831 |         |         |       |

Regression Equation for MRR in Uncoded Units –

$$\begin{aligned} \text{MRR} = & -58.2 + 0.000410 \text{ PRESSURE} + 0.678 \text{ SOD} + 8.67 \text{ ND/MFA} - 5.64 \text{ QOC} + \\ & 0.000000 \text{ PRESSURE*PRESSURE} - 0.0043 \text{ SOD*SOD} \\ & - 0.2868 \text{ ND/MFA*ND/MFA} + 0.527 \text{ QOC*QOC} - 0.000048 \text{ PRESSURE*SOD} + \\ & 0.000004 \text{ PRESSURE*ND/MFA} - 0.000017 \text{ PRESSURE*QOC} \\ & + 0.0256 \text{ SOD*ND/MFA} + 0.2161 \text{ SOD*QOC} - 0.0240 \text{ ND/MFA*QOC} \end{aligned}$$

### 3.4.3 Response Surface Regression: for Circularity

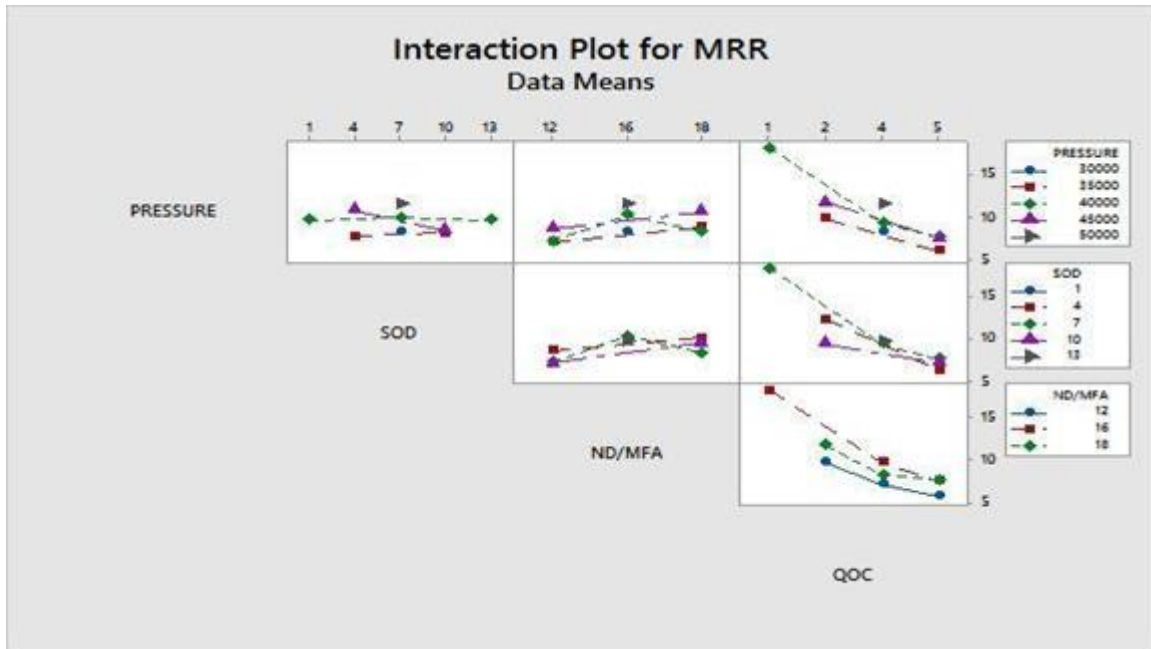
**Table 10.** Analysis of Variance of circularity

| Source            | DF | Adj SS   | Adj MS   | F-Value | P-Value |
|-------------------|----|----------|----------|---------|---------|
| Model             | 14 | 0.002793 | 0.000200 | 3.26    | 0.013   |
| Linear            | 4  | 0.001342 | 0.000336 | 5.48    | 0.006   |
| PRESSURE          | 1  | 0.000516 | 0.000516 | 8.42    | 0.010   |
| SOD               | 1  | 0.000379 | 0.000379 | 6.19    | 0.024   |
| ND/MFA            | 1  | 0.000368 | 0.000368 | 6.00    | 0.026   |
| QOC               | 1  | 0.000080 | 0.000080 | 1.30    | 0.270   |
| Square            | 4  | 0.000501 | 0.000125 | 2.04    | 0.136   |
| PRESSURE*PRESSURE | 1  | 0.000006 | 0.000006 | 0.09    | 0.766   |
| SOD*SOD           | 1  | 0.000389 | 0.000389 | 6.34    | 0.023   |
| ND/MFA*ND/MFA     | 1  | 0.000024 | 0.000024 | 0.40    | 0.537   |
| QOC*QOC           | 1  | 0.000076 | 0.000076 | 1.24    | 0.281   |
| 2-Way Interaction | 6  | 0.000752 | 0.000125 | 2.05    | 0.118   |
| PRESSURE*SOD      | 1  | 0.000033 | 0.000033 | 0.54    | 0.473   |
| PRESSURE*ND/MFA   | 1  | 0.000253 | 0.000253 | 4.13    | 0.059   |
| PRESSURE*QOC      | 1  | 0.000128 | 0.000128 | 2.09    | 0.167   |
| SOD*ND/MFA        | 1  | 0.000132 | 0.000132 | 2.15    | 0.162   |
| SOD*QOC           | 1  | 0.000169 | 0.000169 | 2.76    | 0.116   |
| ND/MFA*QOC        | 1  | 0.000013 | 0.000013 | 0.21    | 0.651   |
| Error             | 16 | 0.000980 | 0.000061 |         |         |
| Lack-of-Fit       | 10 | 0.000741 | 0.000074 | 1.86    | 0.232   |
| Pure Error        | 6  | 0.000239 | 0.000040 |         |         |
| Total             | 30 | 0.003773 |          |         |         |

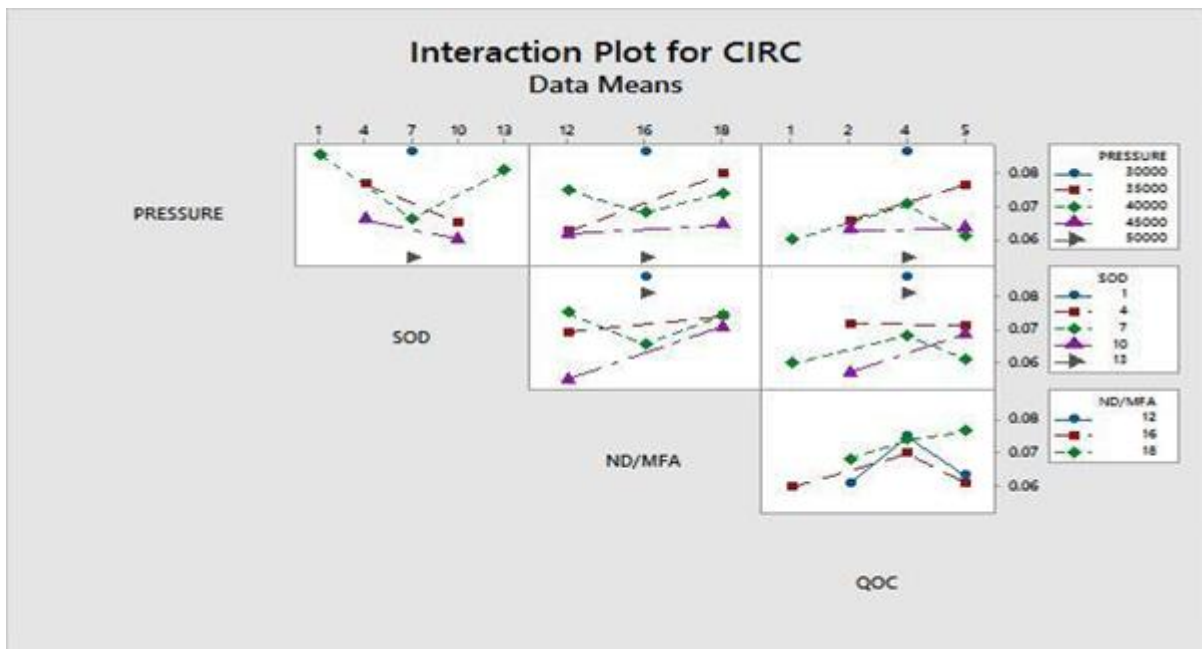
Regression Equation of circularity in Uncoded Units

$$\begin{aligned} \text{CIRC} = & 0.053 + 0.000002 \text{ PRESSURE} - 0.01811 \text{ SOD} + 0.0012 \text{ ND/MFA} + 0.0185 \text{ QOC} \\ & + 0.000000 \text{ PRESSURE*PRESSURE} + 0.000411 \text{ SOD*SOD} \\ & + 0.000261 \text{ ND/MFA*ND/MFA} - 0.00146 \text{ QOC*QOC} + 0.000000 \text{ PRESSURE*SOD} - \\ & 0.000000 \text{ PRESSURE*ND/MFA} - 0.000000 \text{ PRESSURE*QOC} + 0.000313 \text{ SOD*ND/MFA} \\ & + 0.000710 \text{ SOD*QOC} + 0.000198 \text{ ND/MFA*QOC} \end{aligned}$$

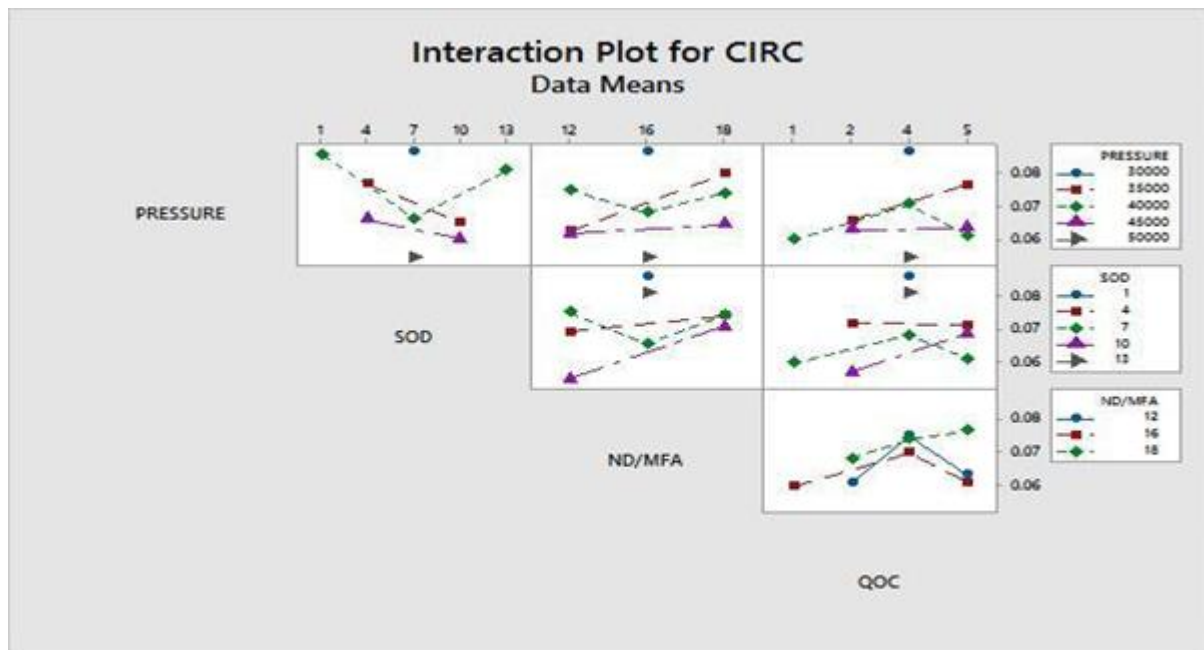
The interaction plot for the Material Removal Rate, Surface Roughness, and Circularity was plotted using the Minitab software and they were utilized to understand the interactions between the various input parameters and the corresponding output parameter in figure 6,7 and 8



**Figure 6.** Interaction plot for MRR.



**Figure 7.** Interaction plot for Circularity



**Figure 8.** Interaction plot for Surface Roughness.

### 3.5 Regression equation and model.

In statistical modelling, regression analysis is a statistical process for estimating the relationships among variables. A regression equation is used to predict the value of the required variable with the help of independent variables. Multiple regression is an extension of simple linear regression. It is used when we want to predict the value of a variable based on the value of two or more other variables. The variable we want to predict is called the dependent variable (or sometimes, the outcome, target or criterion variable).

A residual plot is a graph that shows the residuals on the vertical axis and the independent variable on the horizontal axis. If the points in a residual plot are randomly dispersed around the horizontal axis, a linear regression model is appropriate for the data; otherwise, a non-linear model is more appropriate. The residual graphs for MRR and Circularity, and Surface roughness were plotted using the Minitab software and these plots were then used to observe the fitting of the reading obtained to our current model that can be seen in figure 9, 10 and 11.

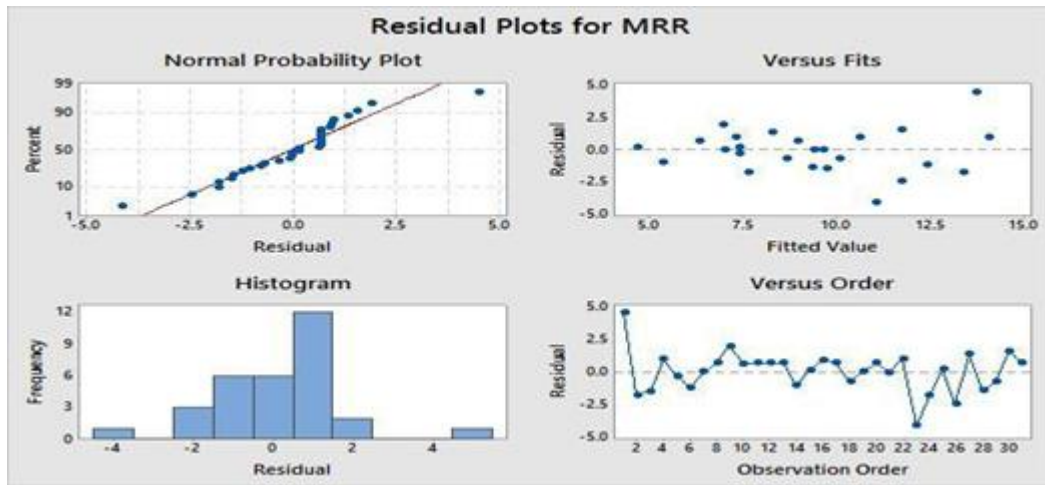


Figure 9. Residual Plots for Material Removal Rate.

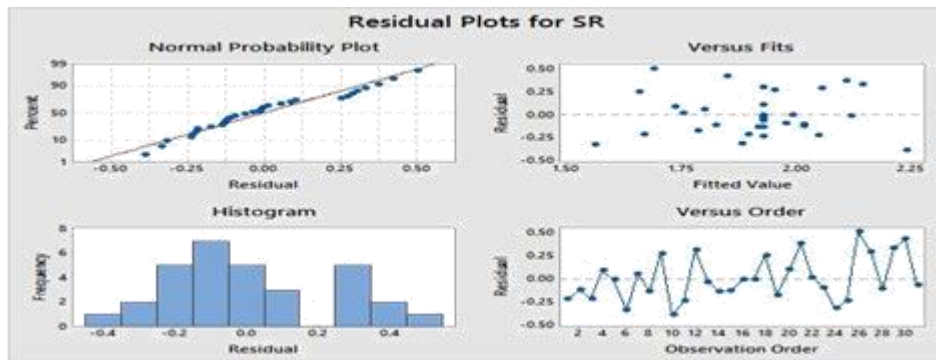


Figure 10. Residual Plots for Circularity.

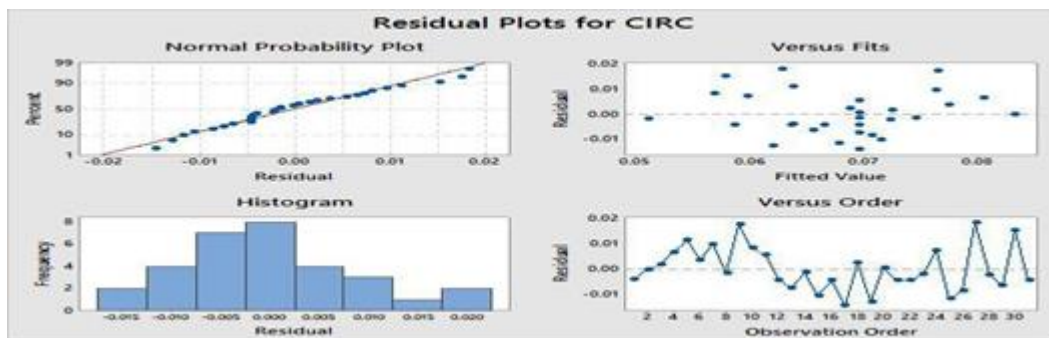
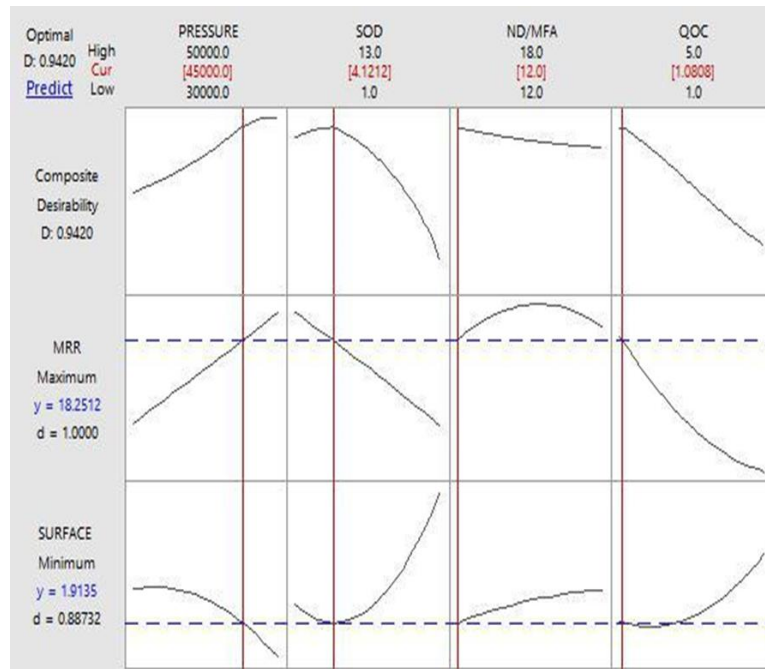
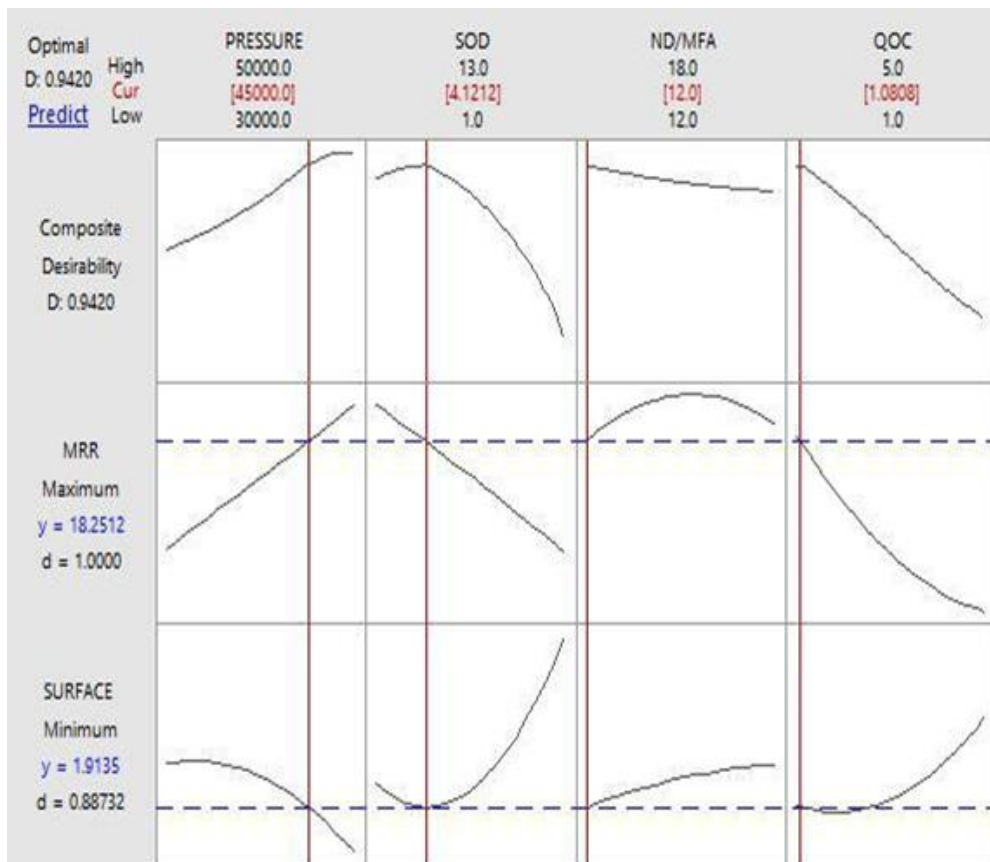


Figure 11. Residual Plots for Circularity.



**Figure 12.** Residual plot for surface roughness.



**Figure 13.** Multi response optimisation predictor graph.



Using the Minitab software we calculated the linear regression equation for the response variables which are as follows-

1. Regression Equation for Surface Roughness –

$$\text{SR} = 1.93 + 0.000050P - 0.113S - 0.087N - 0.266Q + 0.000000P*P + 0.00625S*S \\ + 0.00107N*N - 0.0230Q*Q - 0.000008 P*S - 0.000004P*N + 0.000005 P*Q + 0.02212 S*N \\ + 0.00604 S*Q + 0.01713 N*Q$$

2. Regression Equation for Material Removal Rate –

$$\text{MRR} = -58.2 + 0.000410P + 0.678S + 8.67N - 5.64 Q + 0.000000 P*P - 0.0043 S*S - 0.2868 N*N + \\ 0.527 Q*Q - 0.000048 P*S + 0.000004 P*N - 0.000017 P*Q + 0.0256 S*N + 0.2161 S*Q - 0.0240 \\ N*Q$$

3. Regression Equation for Circularity –

$$\text{CIRC} = 0.053 + 0.000002P - 0.01811S + 0.0012N + 0.0185Q + 0.000000P*P + 0.000411S*S \\ + 0.000261N*N - 0.00146Q*Q + 0.000000 P*S - 0.000000P*N - 0.000000P*Q + 0.000313 \\ S*N + 0.000710S*Q + 0.000198 N*Q$$

### 3.6 Multi response optimisation using anova predictor plot.

Multi response optimisation is the process of determining the optimum value of the input variables by finding the most desirable fit of the output responses that can be seen in figure 12.

A desirability function is created for each process output, with multiple outputs combined into an overall desirability using adjustable weights for each output. From the graph it can be stated that the multi response optimal process parameters are pressure at 45000 psi, standoff distance at 4 mm, nozzle diameter at 12mm, and quality of cut at 1.

### 3.7 Conformity test.

**Table 11.** Conformity table for MRR.

| PRESSURE | SOD | N  | QOC | TH MRR  | EXP MRR | ERROR       |
|----------|-----|----|-----|---------|---------|-------------|
| 45000    | 4   | 14 | 2   | 15.0435 | 14.5465 | 3.303752451 |

**Table 12.** Conformity table for SR.

| PRESSURE | SOD | N  | QOC | TH SR  | EXP SR | ERROR       |
|----------|-----|----|-----|--------|--------|-------------|
| 45000    | 4   | 14 | 2   | 1.5475 | 1.4812 | 4.284329564 |

**Table 13.** Conformity table for Circularity.

| PRESSURE | SOD | N  | QOC | TH CIRC | EXP CIRC | ERROR       |
|----------|-----|----|-----|---------|----------|-------------|
| 45000    | 4   | 14 | 2   | 0.087   | 0.083    | 4.597701149 |

## 4. Conclusions

In the conclusion for the study, we carried out a conformity test on the work piece in accordance with the Grey relation values obtained. The values of MRR, SR, Circularity were calculated to give their experiment values at the optimal level of input parameters. These values were then compared with the actual theoretical values and the error percentage was found out to be conforming to the 5% standard allowance. The error percentage for material removal rate was found to be at 3.303%, and was well within the error allowance. The error percentage for surface roughness was found to be at 4.28%, and was well within the error allowance. The error percentage for circularity was found to be at 4.597%, and was well within the error allowance.

In this paper an experimental study on material removal rate, surface roughness, circularity by abrasive water jet machining of Monel K400 nickel alloy is presented. The effects of pressure, nozzle diameter, stand-off distance, and quality of cut was studied on MRR, SR, Circularity. Through the due course of the project it was concluded that through the viewpoint of multi variable response optimization techniques like Grey analysis, ANOVA, the Grey rank was found out and this rank denotes the best combination of input parameters. Using the mean grey relation values at distinct levels we concluded that pressure would be optimal at level 3 (45000 psi), standoff distance would be optimal at level 3 (10mm), quality of cut would be optimal at level 1 (1), and the nozzle diameter would be optimal at level 2 (14mm) as their respective mean grey values are of the highest level. It was also observed that the difference between mean Grey relation value ranges is maximum for the quality of cut at 0.075. Due to which we are able to concur that the quality of cut is the most influencing parameter in our machining process. Also using ANOVA MRO predictor plot, in our experiment we have utilized the goal of maximizing the response of MRR value at 18.2512 g/min, as higher is the MRR value, the machining process will be much faster, and as a result the cycle time will be less. At the same time we have also utilized the goal of minimizing the response of Surface Roughness at 1.9135 um so as to obtain a smoother finish and distinct, defined machined surface. Confirmation test done in the optimal parameters list in table 11, 12 and 13.

## 5. References

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