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# Parametric Optimization of Abrasive Water Jet Machining Using Taguchi Grey Relational Analysis and Response Surface Methodology

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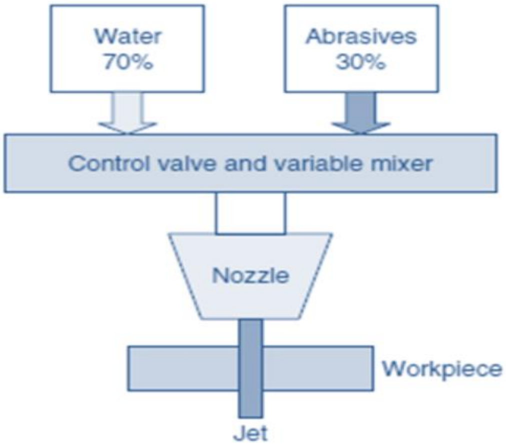
## ABSTRACT

The project deals with optimization of the Abrasive Water Jet Machining of Titanium alloy grade2. Traverse speed, Abrasive flow rate and Standoff distance are considered as process parameters and their effect on performance measures i.e. Material removal rate (MRR) and Surface roughness (SR) will be studied through experimental investigation. Grey relational analysis will be applied to generate grey relational grade to identify the optimum process parameters. These optimum parameters can be adjusted to improve performances of AWJM. Finally Response Surface Methodology is applied to generate a mathematical model of each response.

**Key Words:** Surface Roughness (Ra), Material removal rate (MRR), Taguchi Grey relational analysis, Response surface methodology, Traverse speed, Abrasive flow rate, Standoff distance.

## INTRODUCTION

The term abrasives are used in machining processes such as abrasive jet machining and ultrasonic machining but usage of abrasives differs based on area of work. In AJM air is driven with abrasive to strike the work piece while in USM abrasive grains in liquid slurry and it strikes the work piece at ultrasonic frequency. Recently developments were processed in jet cutting technology by using abrasive water jets with water as a carrier fluid. The mechanical energy of water and abrasive particles are used to achieve material removal. The schematic diagram of abrasive water jet machining is shown in figure. In abrasive water jet machining water and a stream of abrasives from two different directions mix up and pass through jet nozzle where a part of momentum of water jet is transferred to abrasives, which results in increase in velocity and material is removed through erosion at upper most position of work piece whereas at depth by deformation wear. As mentioned earlier, the abrasives are gradually released into the water jet where the momentum transfer takes place from water to abrasive particles. Finally the abrasive particles achieve the acceleration of jet and comes out at which the velocity is assumed to be same.



**Schematic view of AWJM**

## OPERATIONS ON ABRASIVE WATER JET MACHINING

Based on the applications some of the recent developments in operations using AWJM are listed below.

1) Straight line cutting
2) Turning
3) Curved and corner cutting
4) Honey comb cutting
5) Segmental turning
6) Small hole drilling
7) Polishing
8) Water slicing

## LITERATURE SURVEY

**B. Satyanarayan and G. Srikar, [1]** Investigated work on optimization of abrasive water jet machining process parameters using taguchi grey relational analysis (TGRA). The process parameters chosen are abrasive flow rate, pressure, and standoff distance. From ANOVA it is found that water jet pressure has more significant effect on kerf width and MRR rather than abrasive flow rate and standoff distance. They predicted S/N ratio; and found that TGRA process adopted for optimization of parameters is accurate.

**M.A. Azmir, A. K. Ahsan, A. Rahmah, M.M. Noor, and A. A. Aziz [2]** conducted an experiment on the optimization of AWJM on Kevlar with multiple performance characteristics using GRA. They concluded that the performance characteristics of the AWJM process namely hydraulic pressure, abrasive flow rate, standoff distance and traverse rate are improved together by using grey relational analysis.

**P. P. Badgujar, M. G. Rathi [3]** optimized the input parameters of AWJM, such as pressure within pumping system, abrasive material grain size, standoff distance, nozzle speed and abrasive mass flow rate for machining SS304. The Taguchi design of experiment, the signal-to-noise ratio, and analysis of variance are employed to analyze the effect of the input parameters by adopting L27 Taguchi orthogonal array (OA). In order to achieve the minimum surface roughness (SR), five controllable factors, i.e. the parameters of each at three levels are applied for determining the optimal combination of factors and levels. The results reveal that the SR is greatly influenced by the abrasive material grain size. Experimental results affirm the effectiveness of the solving the stated problem within minimum number of experiments as compared to that of full factorial design.

**M. Sreenivasa Rao, S.Ravinder and A. Seshu Kumar [4]** investigated the effect of parameters, viz water pressure, traverse speed, and standoff distance, of abrasive water jet machining (AWJM) for mild steel (MS) on surface roughness (SR). Further Taguchi method analysis of variance and signal to noise ratio (SN Ratio) are used to optimize the considered parameters of abrasive water jet machining. In Taguchi design of experimentation $L_9$ orthogonal array is formulated and it can be concluded that water pressure and traverse speed are the most significant parameters and standoff distance is sub significant parameter.

**Ajay D Kumbhar, Manavendra Chattterjee [5**] have studied the influence of Abrasive water jet machining process parameters using Response surface method while machining Inconel -188.

**K. S. Jai Aultrin and M. Dev Anand [6**] tried for optimization of machining parameters in abrasive water jet machining (AWJM) process for Copper-Iron alloy using RSM and Regression analysis. The process parameters considered were water pressure, abrasive flow rate, orifice diameter focusing nozzle diameter and standoff distance. They studied the effect of five process parameters on metal removal rate (MRR) and surface roughness (SR) of the Copper Iron alloy using regression analysis.

**M. Chithirai pon selvanet al [7]** found that Abrasive water jet cutting is one of the non-traditional cutting processes capable of cutting wide range of hard to-cut materials. They understood the influence of process parameters on the depth of cut which is an important cutting performance measures in abrasive water jet cutting of Stainless Steel. The process variables considered here include Traverse speed, Abrasive flow rate, Standoff distance and water pressure. In order to correctly select the process parameters, prediction of depth of cut in abrasive water jet machining of stainless steel is done by developing an empirical model using regression analysis.

**N. Mohana Sundara Raja et al [8]** formulated the effective technology for processing various engineering materials. Surface roughness of machined parts is one of the major machining characteristics that play an important role in determining the quality of engineering components. This paper assesses the influence of process parameters on surface roughness which is an important cutting performance measure in abrasive water jet cutting of cast Iron. Taguchi design of experiments was carried out in order to collect surface roughness values. Experiments were conducted while varying water pressure, nozzle traverse speed, abrasive flow rate, and standoff distance for cutting cast Iron using abrasive water jet cutting process.

## OBJECTIVES:

The objectives of the present work:

1. To study about the influence of Abrasive water jet machining on Titanium alloy grade 2.
2. To design a series of experiment using the help of Design of Experiments (DOE) layout in order to study Abrasive water jet machining (AWJM).
3. To study about the best combination of solution for maximizing the Material Removal Rate and for minimizing the Surface Roughness with Grey Taguchi analysis, Response Surface methodology.

## OPTIMIZATION OF AWJM THROUGH TAGUCHI GREY RELATIONAL TECHNIQUE

**Factors and levels of experiments**

| Factors | Units | Level1 | Level2 | Level3 |
|---|---|---|---|---|
| **Traverse speed** | **(mm/min)** | 350 | 450 | 650 |
| **Abrasive flow rate** | **(gram/min)** | 320 | 435 | 615 |
| **Standoff distance** | **(mm)** | 1 | 1.5 | 2 |

**Experimental input parameters**

| Exp.no | Traverse Speed | Abrasive Flow Rate | Standoff Distance |
|---|---|---|---|
| 1 | 350 | 320 | 1 |
| 2 | 350 | 435 | 1.5 |
| 3 | 350 | 615 | 2 |
| 4 | 450 | 320 | 1.5 |
| 5 | 450 | 435 | 2 |
| 6 | 450 | 615 | 1 |
| 7 | 650 | 320 | 2 |
| 8 | 650 | 435 | 1 |
| 9 | 650 | 615 | 1.5 |

**L9 Orthogonal Array Design of Experiments**

| Exp. No | Traverse speed (mm/min) | Abrasive flow rate (gram/min) | Standoff distance (mm) | Surface roughness (µm) | MRR ($mm^3$/min) |
|---|---|---|---|---|---|
| 1 | 350 | 320 | 1 | 1.6713 | 2.04813 |
| 2 | 350 | 435 | 1.5 | 2.3293 | 1.6667 |
| 3 | 350 | 615 | 2 | 2.8932 | 1.24183 |
| 4 | 450 | 320 | 1.5 | 2.5486 | 0.8848667 |
| 5 | 450 | 435 | 2 | 3.1270 | 1.695156 |

| | | | | | |
|---|---|---|---|---|---|
| 6 | 450 | 615 | 1 | 3.00023 | 1.657828 |
| 7 | 650 | 320 | 2 | 2.9356 | 2.91938 |
| 8 | 650 | 435 | 1 | 3.1636 | 2.73414 |
| 9 | 650 | 615 | 1.5 | 3.2647 | 1.5815 |

**Signal to noise ratio of MRR and SR**

| Exp. No | S/n Ratio of MRR | S/n Ratio of SR |
|---|---|---|
| 1 | 6.22715 | -4.4611 |
| 2 | 4.43699 | -7.3445 |
| 3 | 1.88124 | -9.2276 |
| 4 | -1.06244 | -8.1260 |
| 5 | 4.58419 | -9.9026 |
| 6 | 4.39079 | -9.5491 |
| 7 | 9.30584 | -9.3539 |
| 8 | 8.73644 | -10.0036 |
| 9 | 3.98138 | -10.2769 |

**Normalized values of Grey Relational Generation for MRR & SR**

| **Exp.no** | **MRR ($mm^3$/min)** | **SR (Ra)** |
|---|---|---|
| **1** | 0.5718 | 1 |
| **2** | 0.3842 | 0.587 |
| **3** | 0.1754 | 0.233 |
| **4** | 0.00 | 0.449 |
| **5** | 0.398 | 0.0864 |
| **6** | 0.3799 | 0.1646 |
| **7** | 1 | 0.206 |
| **8** | 0.9089 | 0.0634 |
| **9** | 0.3424 | 0.00 |

**Grey relational coefficient of each performance characteristic (=0.5)**

| **Exp.no** | **MRR ($mm^3$/min)** | **SR (Ra)** |
|---|---|---|
| 1 | 0.4282 | 0 |
| 2 | 0.6158 | 0.413 |
| 3 | 0.8246 | 0.767 |
| 4 | 1 | 0.551 |
| 5 | 0.602 | 0.9136 |
| 6 | 0.6021 | 0.8354 |
| 7 | 0.00 | 0.794 |
| 8 | 0.0911 | 0.9366 |

| | | |
|---|---|---|
| 9 | 0.6576 | 1 |

The Grey relational grade is computed by averaging the grey relational coefficients corresponding to each process response. The overall evaluation of the multiple process response is based on the grey relational grade. High Grey relational grade gives the optimal solutions. After data pre-processing is carried out, a grey relational coefficient can be calculated with the pre-processed sequence. It expresses the relationship between the ideal and actual normalized experimental results. The grey relational coefficient is defined by equation.

$$\xi_i\,(k) = \frac{\Delta min+\xi.\Delta\max}{\Delta o_i+\xi.\Delta max}$$

Where $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence $x_o^*(k)$ and the comparability sequence is $x_i^*(k)$, ξ distinguishing or identification coefficient. If all the parameters are given equal preference, is taken as 0.5. The grey relational coefficient for each experiment of the L9 OA can be calculated using Equation 6 and the same is presented in Table

**Grey relational coefficients**

| **Exp. no** | **SR $\xi_i$ (1)** | **MRR $\xi_i$ (2)** |
|---|---|---|
| **1** | **1** | **0.5386** |
| 2 | 0.5476 | 0.4480 |
| 3 | 0.3946 | 0.3774 |
| 4 | 0.4757 | 0.3333 |
| 5 | 0.3537 | 0.4537 |
| 6 | 0.3744 | 0.446 |
| 7 | 0.3863 | 1 |
| 8 | 0.348 | 0.8458 |
| 9 | 0.3333 | 0.4319 |

### Grey Relational Grade:

The grey relational grade is computed by averaging the grey relational coefficients corresponding to each process response. The overall evaluation of the multiple process responses is based on the grey relational grade. High Grey relational grade gives the optimal solutions.

The grey relational grade is obtained by equation.

$$\gamma_i = \frac{1}{2}\,[\xi_i(1) + \xi_i(2)]$$

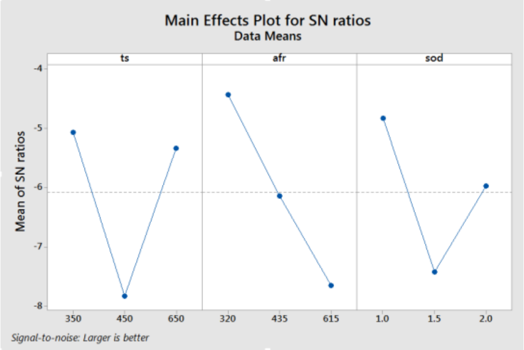
**Overall grey relational grades**

| **Exp.no** | **Grey Relational Grade $\gamma_i$** | **Rank** |
|---|---|---|
| **1** | **0.7693** | **1** |
| 2 | 0.4978 | 4 |
| 3 | 0.4535 | 8 |
| 4 | 0.4045 | 6 |
| 5 | 0.4037 | 7 |
| 6 | 0.402 | 5 |
| 7 | 0.69315 | 2 |
| 8 | 0.5969 | 3 |

| | | |
|---|---|---|
| 9 | 0.3826 | 9 |

**Average of Grey Relational Grades**

| Machining Parameters | Grey Relational Grade | | | Main Effect (max-min) | Rank |
|---|---|---|---|---|---|
| | Level 1 | Level 2 | Level 3 | | |
| **Transverse Speed** | 0.5735 | 0.4061 | 0.55755 | 0.1674 | 2 |
| **Abrasive Flow Rate** | 0.622 | 0.4994 | 0.4154 | 0.2066 | 1 |
| **Standoff Distance** | 0.5185 | 0.5337 | 0.4849 | 0.0488 | 3 |



**Main affects plots for S/N ratio GRG**

**ANOVA for GRG, using Adjusted SS for tests**

| Source | Df | Adj.SS | Adj.MS | F-Value | P-Value | % C |
|---|---|---|---|---|---|---|
| **Traverse speed** | 2 | 1.08339 | 0.54169 | 21.63 | 0.044 | 52.25% |
| **Abrasive flow rate** | 2 | 0.71608 | 0.35804 | 14.29 | 0.065 | 34.54% |
| **Standoff distance** | 2 | 0.22353 | 0.11176 | 4.46 | 0.183 | 10.78% |
| **Error** | 2 | 0.05009 | 0.02505 | | | 2.33% |
| **Total** | 8 | 2.07308 | | | | |

The optimal grey relational grade (GRGopt) is predicted by using the equation.

$$GRG_{opt} = GRG_{mean} + \sum_{i=1}^{n}(GRG_i - GRG_{mean})$$

Where GRGmean is the average of Grey relational grade, GRGi is the average of grey relational analysis at optimum level and n is the significantly affecting process parameters. The predicted value of optimal grey relational grade is expressed by taking n = 3 since there are three significant parameters. The predicted value of optimal Grey Relational Grade is calculated as:

$$GRG_{OPT} = 0.504090 + (0.5575-0.504090) + (0.622 - 0.504090) + (0.5337-0.504090)$$
$$= 0.7036$$

**Gives the predicted and experimental values of grey relational grade**

| **Optimal Process Parameters** | **Predicted value** | **Experimental value** |
|---|---|---|
| **Levels** | A1B1C1 | A1B1C1 |
| **MRR** | 2.853 | 2.0481 |
| **SR** | 1.7528 | 1.6713 |
| **GRG** | 0.7036 | 0.7693 |

**Summary:**

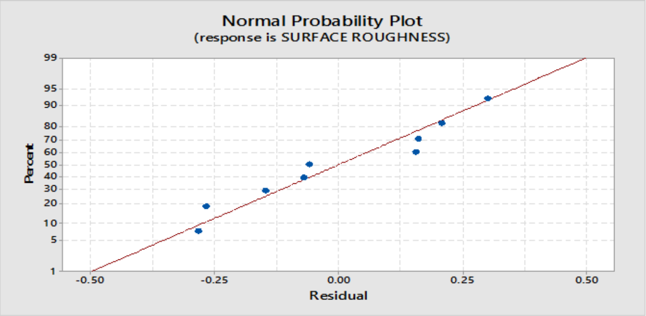
This chapter reviews the results in graphical form and explains about influence of process parameters on target measure. This information is carried forward in chapter 5 for the equation and optimization.

## PREDICTIVE MODELS FOR MRR AND SR THROUGH RESPONSE SURFACE METHODOLOGY (RSM)

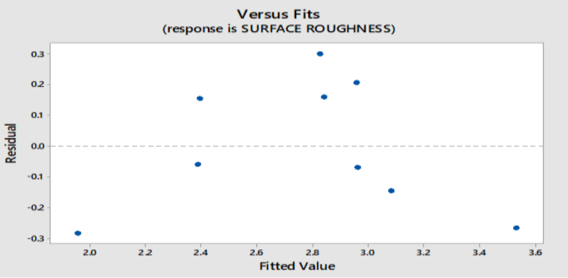
**Data for Response surface methodology Outputs**

| **Run** | **INPUTS** | | | **OUTPUTS** | |
|---|---|---|---|---|---|
| | Traverse Speed (mm/min) | Abrasive Flow Rate (gram/min) | Standoff Distance (mm) | $R_a$ (µm) | MRR ($mm^3$/min) |
| 1 | 350 | 320 | 1 | 1.6713 | 2.04813 |
| 2 | 350 | 435 | 1.5 | 2.3293 | 1.6667 |
| 3 | 350 | 615 | 2 | 2.8932 | 1.24183 |
| 4 | 450 | 320 | 1.5 | 2.5486 | 0.8848667 |
| 5 | 450 | 435 | 2 | 3.1270 | 1.695156 |
| 6 | 450 | 615 | 1 | 3.00023 | 1.657828 |
| 7 | 650 | 320 | 2 | 2.9356 | 2.91938 |
| 8 | 650 | 435 | 1 | 3.1636 | 2.73414 |
| 9 | 650 | 615 | 1.5 | 3.2647 | 1.5815 |

**Response surface methodology for surface roughness**



Normal Probability Plot for Surface Roughness



Residual plot for surface roughness

Analysis of variance for surface roughness

| Source | DF | SS | MS | F-value | P-value | %C |
|---|---|---|---|---|---|---|
| **Model** | 3 | 1.7099 | 0.56997 | 7.83 | 0.025 | 82.44% |
| **Linear** | 3 | 1.7099 | 0.56997 | 7.83 | 0.025 | 82.44% |
| **Traverse speed** | 1 | 0.8861 | 0.88611 | 12.17 | 0.018 | 42.72% |
| **Abrasive flow rate** | 1 | 0.6153 | 0.61526 | 8.45 | 0.034 | 29.66% |
| **Standoff distance** | 1 | 0.2085 | 0.20854 | 2.86 | 0.151 | 17.55% |
| **Error** | 5 | 0.3641 | 0.07283 | | | 10.00% |
| **Total** | 8 | 2.0740 | | | | |
| **R-sq**=82.44% | | | | | | |
| S=0.269863 | | **R-sq (adj)** = 71.91% | | | **R-sq(pred)** = 36.04% | |

The estimated model fits the data can be measured by the value of $R^2$. The $R^2$ lies in the interval [0, 1]. When $R^2$ is closer to the 1, the better the estimation of regression equation fits the sample data. In general $R^2$ measures percentage of the variation is explained by the regression equation. However, adding a variable to the model always increased $R^2$ is statistically significant.

**Coded coefficients of Surface Roughness:**

Coded Coefficients of Surface Roughness

| Term | Effect | Coef | Se Coef | T-value | P-value | VIF |
|---|---|---|---|---|---|---|
| **Constant** | | 2.8359 | 0.0911 | 31.13 | 0.000 | |
| **Traverse speed** | 0.755 | 0.377 | 0.108 | 3.49 | 0.018 | 1.00 |
| **Abrasive flow rate** | 0.635 | 0.318 | 0.109 | 2.91 | 0.034 | 1.00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Standoff distance** | 0.373 | 0.186 | 0.110 | 1.69 | 0.1510 | 1.00 |

The final response equation for Surface roughness is given as follows

Surface roughness = 0.012+0.002516(Traverse speed) +0.002154(Abrasive flow rate) +0.373(Standoff distance)

**Analysis of variance of material removal rate**

| Source | DF | SS | MS | F-Value | P-Value | %C |
|---|---|---|---|---|---|---|
| **Model** | 3 | 2.8143 | 0.93811 | 12.85 | 0.009 | 88.51% |
| **Linear** | 3 | 2.8143 | 0.93811 | 12.85 | 0.009 | 88.51% |
| **Traverse speed** | 1 | 2.3598 | 2.3598 | 32.31 | 0.002 | 74.21% |
| **Abrasive flow rate** | 1 | 0.3228 | 0.32277 | 4.42 | 0.089 | 10.15% |
| **Standoff distance** | 1 | 0.1317 | 0.13175 | 1.80 | 0.237 | 4.14% |
| **Error** | 5 | 0.3651 | 0.07303 | | | 11.48% |
| **Total** | 8 | 3.1795 | | | | |
| R-sq = 88.52% | | | | | | |
| S = 0.270238 | | R- sq (adj) = 81.62% | | | R- sq (pred) = 68.99% | |

The estimated model fits the data can be measured by the value of $R^2$. The $R^2$ lies in the interval [0, 1]. When $R^2$ is closer to the 1, the better the estimation of regression equation fits the sample data. In general $R^2$ measures percentage of the variation is explained by the regression equation. However, adding a variable to the model always increased $R^2$ is statistically significant.

**Coded Coefficients of Material Removal Rate:**

**Coded Coefficients of Material Removal Rate**

| Terms | Effect | Coef | Se Coef | T-Value | P-Value | VIF |
|---|---|---|---|---|---|---|
| **Constant** | | 2.0534 | 0.0912 | 22.51 | 0.000 | |
| **Traverse speed** | 1.232 | 0.616 | 0.108 | 5.68 | 0.002 | 1.00 |
| **Abrasive Flow rate** | -0.460 | -0.230 | 0.109 | -2.10 | 0.089 | 1.00 |
| **Standoff Distance** | -0.2960 | -0.148 | 0.110 | -1.34 | 0.237 | 1.00 |

The final response equation for Material removal rate is given as follows

MRR = 1.174 + 0.004106 (Traverse speed) - 0.001560(Abrasive flow rate) - 0.296(Standoff distance)

**Fits and Diagnostics for Unusual Observations Material Removal rate**

| Obs | MRR | Fit | Residual | STD Residual |
|---|---|---|---|---|
| 4 | 1.587 | 2.078 | -0.492 | -2.11 |

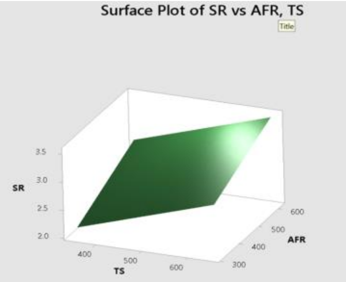
**Summary:**

In this chapter reviews the results about Response Surface methodology by using Minitab software and explain about influence of process parameters on the performance measures. This information is carried forward in chapter 6 for the optimization for response surface plots

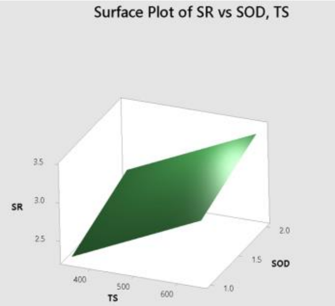
# RESULTS AND DISCUSSIONS

## RESPONSE SURFACE PLOTS OF SURFACE ROUGHNESS

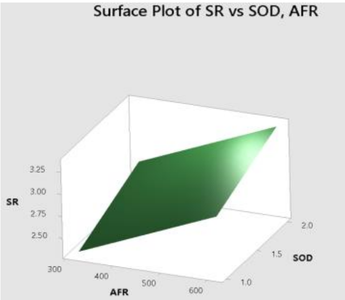
Traverse speed vs. abrasive flow rate



Traverse speed vs standoff distance:

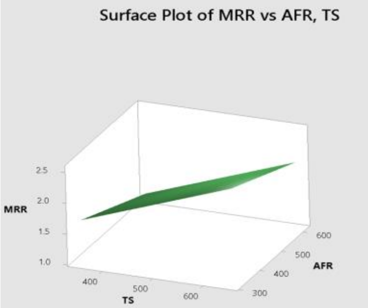


Abrasive flow rate vs standoff distance:

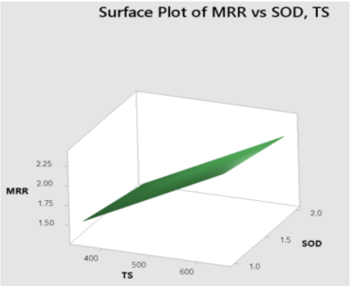


## RESPONSE SURFACE PLOTS OF MATERIAL REMOVAL RATE

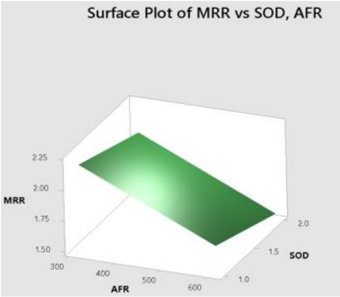
Traverse speed vs abrasive flow rate:



Traverse speed vs standoff distance:



Abrasive flow rate vs. standoff distance:



## CONCLUSION

For the present project the parameters that are controlled by the machine operator when performing the abrasive water jet machining process have been investigated with the aim of selecting the combination of values for these parameters that will generate the optimum combination of the machining parameters obtained from Taguchi Grey relational analysis. Furthermore these same parameter and their values were employed to conduct nine experiments as demonstrated in table 5.2 which will provide the data for Response surface methodology that will generate a prediction model for the material removal rate and surface roughness that will be used to check the experiment results optimum parameter values given by taguchi grey relational method. The conformation experiments were performed with the optimum combination of the machining parameters obtained from GRA Technique. The mentioned parametric combinations for material removal rate are A1B1C1 and after confirmation test the optimum response value of MRR is 2.853 grams/min. The conformation experiments were performed on Surface roughness with A1B1C1 levels as obtained from GRA Technique. The optimal value for surface roughness after conformation test is 1.7528µm. These test results offers a greater significant parameters on output parameters such as MRR, SR while machining Titanium alloy Grade 2 material on abrasive water jet machining. From the experimental results an empirical model or the prediction of material removal rate and surface roughness in abrasive water jet cutting process of Titanium alloy grade 2 has been developed using response surface analysis. This model was confirmed and its great consistency and applicability were within experimental range used

- Grey relational analysis in taguchi method for the optimization of multi response problems for predicting the Material removal rate and Surface roughness in abrasive water jet machining of Titanium alloy Grade 2.
- Form this analysis it is revealed that the Traverse speed (52.25%), Abrasive flow rate (34.54%) and Standoff distance (10.78%) which affects the abrasive water jet machining

of Titanium alloy grade 2. The machining parameters set at optimum levels can make certain considerable enhancement in process parameters.

- The optimal parameter values are Traverse speed 350 mm/min; Abrasive flow rate 320 gram/min and standoff distance 1mm. At these parameters the values of MRR and SR are 2.04813 mm$^3$/min and 1.6713µm respectively.
- From the ANOVA F test the optimizing technique, it can be concluded that Traverse speed duration is the most significant factor influencing the responses followed by Abrasive flow rate and Standoff distance.
- Predictive models are developed using Response surface methodology to estimate material removal rate and surface roughness with input process parameters of Traverse speed, Abrasive flow rate and Standoff distance.

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