

Optimization of Process Parameters in Abrasive Water Jet Machining

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ABSTRACT: This paper attempts to select the significant process parameters by Taguchi methodology while machining of STAINLESS STEEL 410 by AWJM. Different process parameters like pressure, feed rate, and standoff distance in three different levels are selected for optimization with three contravene responses, higher MRR and low machining timing by a single parametric combination. For Design of experiment L9 orthogonal array is prepared to set the input significant parameters for final product is calculated for better optimization purpose also different combinations of the factors are ranked on basis of grey relational grade.

I. INTRODUCTION

Abrasive water jet machining also known as a water jet is an industrial tool capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance. The term abrasive jet refers specifically to the use of a mixture of water and abrasive to cut hard materials such as metal or granite, while the terms pure water jet and water-only cutting refer to water jet cutting without the use of added abrasives, often used for softer materials such as wood or rubber. Water jet cutting is often used during fabrication of machine parts. It is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods. Water jet cutting is used in various industries, including mining and aerospace, for cutting, shaping, and reaming. Water jet technology evolved in the post-war era as researchers around the world searched for new methods of efficient cutting systems.

This system used a 100,000 psi (690 MPa) pump to deliver a hypersonic liquid jet that could cut high strength alloys such as PH15-7-MO STAINLESS STEEL 410. Used as a honeycomb laminate on the Mach 3 North American XB-70 Valkyrie, this cutting method resulted in delaminating at high speed, requiring changes to the manufacturing process. While not effective for the XB-70 project, the concept was valid and further research continued to evolve water jet cutting.

1.1 PROCESS

- Uses a high velocity stream of Ultra High Pressure Water 30,000–90,000 psi (210–620 MPa) which is produced by an intensifier pump with possible abrasive particles suspended in the stream.
- Is used for machining a large array of materials, including heat-sensitive, delicate or very hard materials.
- Produces no heat damage to work piece surface or edges.
- Nozzles are typically made of sintered boride.
- Produces a taper of less than 1 degree on most cuts, which can be reduced or eliminated entirely by slowing down the cut process or tilting the jet.
- Distance of nozzle from work piece affects the size of the kerf and the removal rate of material. Typical distance is .125 in (3.2 mm). Temperature is not as much of a factor.

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II. PRINCIPLE OF OPERATION

In injection-abrasive water jet system, abrasive particles as characterized, a high-speed water jet as described and air enter a cutting head from different entries. In the cutting head, these phase are mixed and the abrasive particles and the air are accelerated. As a result, an abrasive water jet is formed in the cutting head. There are several demands that have to be covered by a generation system for abrasive water jet, such as

- Optimum abrasive-particle acceleration
- High energy density of the generated abrasive water jet
- Low wear of the parts of the system, especially of the focus
- Reliable performance
- Simple function



Fig 1.1 AWJM Machine

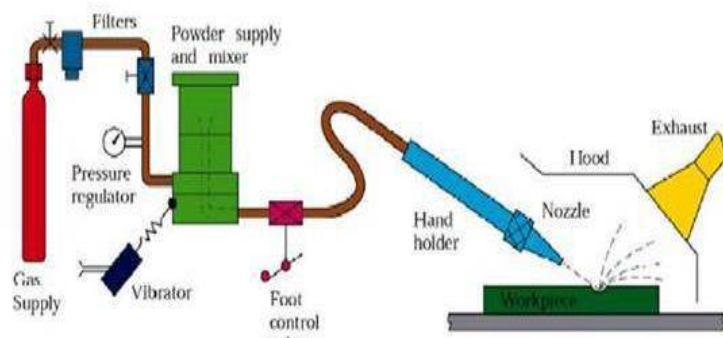


Fig 1.2 Construction of AWJM

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TABLE 1.1 Specification of AWJM machine

| | | |
|------------------------|--|------------------------|
| Length | | 2.5m |
| Wide | | 1.5m |
| Standoff distance | | 1mm – 200mm |
| Pressure | | 600bar – 3800 bar |
| Abrasive particle used | | SiC |
| Cutting speed | | 100mm/s – 1000mm/s |
| Abrasive flow rate | | 100kg/min – 500 kg/min |
| | | |

II. LITERATURE REVIEW

Ruzhong Yan et al , 2014 designed a constrained abrasive jet polishing model. High-speed abrasive jet charges into the clearance between the constrained wheel and optical glass, and a high- energy velocity field has been formed under the centrifugal force of wheel and the hydrodynamic pressure. E Lemma, et. al 2002 developed a new technique which is a variant of the traditional AWJ cutting technique, makes use of a back and forth motion of the cutting head which is superimposed on the normal linear motion to effect optimum loading of the cutting forces on the workpiece material and scan the cut-wall surface to also improve surface finish

K. S. Jai Aultrin at al.,2014 reviewed that past studies have prominent decision variables, objective functions, constraints, variable bounds, remarks and their limitation. The results were recapitulated as follows. Abrasive water jet cutting is one of the newly developed processes by which different types of brittle materials like glass, ceramics and stones, composite materials, ferrous and non-ferrous materials are machined. Based on the paper given by Hashish M., a flow of small abrasive particles is introduced in the water jet and the key role of water is to speed up large quantities of abrasive particles to a high velocity to produce a high coherent jet. This jet is then impacted towards the working surface R. Kovacevic, M. Fang made few attempts have been made to model and optimize the process parameters in AWJC. The approaches employed in this direction include Design of Experiments (DOE), regression modeling, Analysis of Variance (ANOVA), fuzzy logics and artificial neural networks. Some of these studies gave rise to various mathematical equations developed for predicting the output parameters. K.Kalpana et al 2015 reviewed on the research aspects in the condition monitoring of Abrasive Water Jet Machining (AWJM) system. Condition monitoring of the AWJM system helps to achieve an effective utilization of the machine in order to increase productivity. AWJM is one of the non-traditional machining processes used to machine difficult-to-machine materials.

T.Nguyen et al 2015 presented an analysis of the abrasive water jet milling performance. The milled channel characteristics are dominated by nine dimensionless variables representing the process parameters and material properties that govern the channel formation process. Predictive models considering these nine dimensionless variables are then developed for estimating the characteristics of the channels milled by an AWJ. The models are verified and found to agree well with the experimental data.M. M. Korat et al reviewed the research work carried out from the inception to the development of AWJM within the past decade. It reports on the AWJM research relating to improving performance measures, monitoring and control of process, optimizing the process variables. A wide range of AWJM industrial applications for different category of material are reported with variations.

Abhishek Dixit et al examined the role of water jet in heavy construction in general and particularly how it affects the regional contractors in the northeast. A survey was conducted among 215 civil contractors of the Northeast region of the United States and the results were documented in various categories. The paper presents aspects regarding an innovative nonconventional technology, abrasive water jet machining.M.Uthayakumar et al presented an approach with the assessment of the process parameters in abrasive waterjet cutting of redmud reinforced banana/polyester hybrid composite. The composite was prepared through compression molding technique with varying weight percentage of redmud viz. 10%,20% and 30%. Investigation has been conducted to assess the influence of the input

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parameters on the output responses such as material removal rate, top kerf width, bottom kerf width and kerf angle of the composite.

Jiazhong Xu et al conducted experimental research on several typical materials cut by water-jet cutting machine equipped with phased intensifier is conducted, which is valuable for design, manufacture and technological application of high pressure water equipment. It is practically proved that this system can work stably, with fluctuation rate of water pressure no more than 2.0%, as well as good cutting quality and high production efficiency. M.A. Azmir, A.K. Ahsan et al conducted a practical study for analyzing the surface roughness and kerf taper ratio of glass/epoxy composite laminate machined using abrasive water jet machine. The various process parameters considered are abrasive types (2-level), hydraulic pressure (3-level), standoff distance (3-level), abrasive flow rate (3-level), traverse rate (3-level), cutting orientation (3-level). The optimization of AWJM was done with the use of Taguchi method and ANOVA (analysis of variance). The ratio of top kerf width to bottom kerf width is called Kerf taper ratio.

III. PROBLEM IDENTIFICATION

Taguchi method is applied to find optimum process parameter for Abrasive water jet machining (AWJM). Abrasive water jet machining is a non-traditional process of removal of material by impact erosion of high pressure, high velocity of water and entrained high velocity of grit abrasives on a work piece. Experimental investigation were conducted to assess the influence of abrasive water jet machining (AWJM) process parameters on MRR of STAINLESS STEEL. The approach was based on Taguchi's method and analysis of variance (ANOVA) to optimize the AWJM process parameter for effective machining and to predict the optimal choice for each AWJM parameter such as pressure, standoff distance, Abrasive flow rate and Traverse rate. For each combination of orthogonal array we have Conducted three experiments and with the help of ANOVA it is found that these parameters have a significant influence on machining characteristics such as metal removal rate (MRR). The analysis of the Taguchi method reveals that, in general the standoff distance significantly affects the MRR while, Abrasive flow rate affects the surface Roughness. Experiments are carried out using orthogonal array by varying pressure, standoff distance, Abrasive flow rate and Traverse rate respectively. Experimental results are provided to verify this approach.

3.1 Material

In this investigation, the work piece material stainless steel was used with the following main properties: Tensile Strength 90 MPa, Modulus of elasticity 69 GPa, and Density 2.71 g/cm³. The abrasive used was garnet with mesh size of 80 and hardness of 7.5 Mohs.

3.2 Equipment

The equipment used for machining the samples was Abrasive WaterJet Machine of model 2626 OMAX Jet Machining Centre equipped with OMAX High-Pressure Pump with the design pressure of 345MPa (50,000 psi) and the nozzle diameter was 0.75mm. The OMAX variable speed, high-pressure pump is an electrically driven, variable speed, positive displacement, crank shaft drive triplex pump designed for use with the OMAX precision jet machining system and other applications requiring high pressure water required by the OMAX jet machining system to operate. The pump control panel provides a keypad display screen, and pumps start/stop controls. When the pump is attached to an OMAX jet machining centre, controls shared between the Jet machining centre controller and the pump.

3.2.1 Experimental Design:

The experimental layout for the machining parameters using the L₉ orthogonal array was used in this study. This array consists of four control parameters and three levels, as shown in table 1. In the taguchi method, most all of the observed values are calculated based on 'the higher the better' and 'the smaller the better'. Thus in this study, the observed values of MRR, and SR were set to maximum, and minimum respectively. Next experimental trial was performed with three simple replications at each set value.

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Table 1.2 Design Scheme of Experiments for Parameters and Levels

| Control Parameters | Level | | | Observed Values |
|---------------------------|---------|--------------|---------|---|
| | 1 | 2 | 3 | |
| | Minimum | Intermediate | Maximum | Material Removal Rate (mm ³ /min) |
| Pressure,P (MPa) | 155 | 224 | 293 | |
| Stand of distance,S(mm) | 2.5 | 3.5 | 4.5 | |
| Abrasive flow rate,A(g/s) | 4.5 | 6.5 | 8.5 | |
| Traverse rate,T(mm/s) | 1.5 | 2.5 | 3.5 | |

IV. METHODOLOGY

A well planned set of experiments, in which all parameters of interest are varied over a specified range, is a much better approach to obtain systematic data. Mathematically speaking, such a complete set of experiments ought to give desired results. Usually the number of experiments and resources (materials and time) required are prohibitively large. Often the experimenter decides to perform a subset of the complete set of experiments to save on time and money! However, it does not easily lend itself to understanding of science behind the phenomenon. The analysis is not very easy (though it may be easy for the mathematician/statistician) and thus effects of various parameters on the observed data are not readily apparent. In many cases, particularly those in which some optimization is required, the method does not point to the BEST settings of parameters. A classic example illustrating the drawback of design of experiments is found in the planning of a world cup event, say football. While all matches are well arranged with respect to the different teams and different venues on different dates and yet the planning does not care about the result of any match (win or lose)!!!! Obviously, such a strategy is not desirable for conducting scientific experiments (except for coordinating various institutions, committees, people, equipment, materials etc.).

4.1 PROPERTIES OF AN ORTHOGONAL ARRAY

The orthogonal arrays have the following special properties that reduce the number of experiments to be conducted.

1. The vertical column under each independent variables of the above table has a special combination of level settings. All the level settings appear an equal number of times. For L9 array under variable 4, level 1, level 2 and level 3 appears thrice. This is called the balancing property of orthogonal arrays.
2. All the level values of independent variables are used for conducting the experiments.
3. The sequence of level values for conducting the experiments shall not be changed. This means one cannot conduct experiment 1 with variable 1, level 2 setup and experiment 4 with variable 1, level 1 setup. The reason for this is that the arrays of each factor columns are mutually orthogonal to any other column of level values. The inner product of vectors corresponding to weights is zero. If the above levels are normalized between -1 and 1, then the weighing factors for level 1, level 2, level 3 are -1, 0, 1 respectively. Hence the inner product of weighing factors of independent variable 1 and independent variable 3 would be $(-1 * -1 + -1 * 0 + -1 * 1) + (0 * 0 + 0 * 1 + 0 * -1) + (1 * 0 + 1 * 1 + 1 * -1) = 0$

4.2 GREY RELATIONAL ANALYSIS

Grey relational analysis uses a specific concept of information. It defines situations with no information as black, and those with perfect information as white. However, neither of these idealized situations ever occurs in real world problems. In fact, situations between these extremes are described as being grey, hazy or fuzzy. Therefore, a grey

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system means that a system in which part of information is known and part of information is unknown. With this definition, information quantity and quality form a continuum from a total lack of information to complete information – from black through grey to white. Since uncertainty always exists, one is always somewhere in the middle, somewhere between the extremes, somewhere in the grey area.

Grey analysis then comes to a clear set of statements about system solutions. At one extreme, no solution can be defined for a system with no information. At the other extreme, a system with perfect information has a unique solution. In the middle, grey systems will give a variety of available solutions. Grey analysis does not attempt to find the best solution, but does provide techniques for determining a good solution, an appropriate solution for real world problems.

4.3 TAGUCHI METHOD

Taguchi methods are statistical methods developed by Genichi Taguchi to improve the quality of manufactured goods, and more recently also applied to engineering, biotechnology, marketing and advertising. Professional statisticians have welcomed the goals and improvements brought about by Taguchi methods, particularly by Taguchi's development of designs for studying variation, but have criticized the inefficiency of some of Taguchi's proposals.

Taguchi's work includes three principal contributions to statistics:

- A specific loss function
- The philosophy of off-line quality control; and
- Innovations in the design of experiments.

4.3.1 VARIABLES USED

Table 1.3 Variable process parameters

| Process parameters | 1 | 2 | 3 |
|-------------------------|-----|------|-----|
| Pressure (bar) | 600 | 3800 | - |
| Stand off distance (mm) | 1 | 2 | 3 |
| Cutting speed (mm/min) | 150 | 180 | 220 |

Table 1.4 Machining array

| Runs | PRESSURE | SOD | SPEED | MACHINING TIME | MRR | Kerf width |
|------|----------|-----|-------|----------------|-----------|------------|
| Unit | bar | mm | m/sec | sec | cu.mm/sec | mm |
| 1 | 600 | 1 | 150 | 81 | 1.988 | 1.5143 |
| 2 | 600 | 3 | 180 | 70.5 | 2.32 | 1.5632 |
| 3 | 600 | 2 | 180 | 68.5 | 2.913 | 1.5757 |

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| | | | | | | |
|---|------|---|-----|------|-------|--------|
| 4 | 600 | 1 | 220 | 59 | 4.181 | 1.5639 |
| 5 | 3800 | 2 | 180 | 74.5 | 2.329 | 1.5301 |
| 6 | 3800 | 1 | 150 | 77.5 | 8.169 | 1.5335 |
| 7 | 3800 | 2 | 150 | 75 | 6.2 | 1.5274 |
| 8 | 3800 | 3 | 220 | 60 | 2.99 | 1.4723 |
| 9 | 3800 | 3 | 220 | 54.5 | 9.59 | 1.4347 |

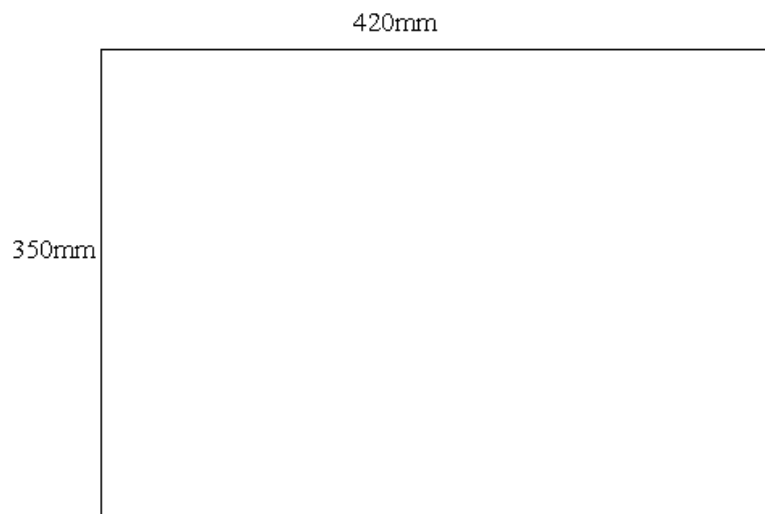
4.3.2 Hardness calculation:

For the SS410 plate all three hardness test were taken.

Table 1.5 Hardness test

| S.No | Brinell Hardness (BHN) | Rockwell Hardness (RHN) | Vickers Hardness (VHN) |
|------|------------------------|-------------------------|------------------------|
| 1 | 96.24 | 85 | 257.5 |
| 2 | 90.6 | 86.3 | 255.9 |

SS410 PLATE



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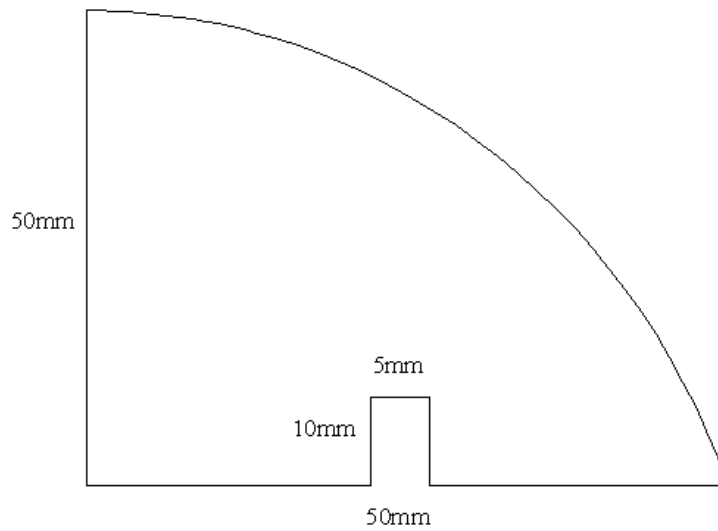


Fig 1.3 Profile for Machining

V. RESULT AND DISCUSSION

5.1 Taguchi Method

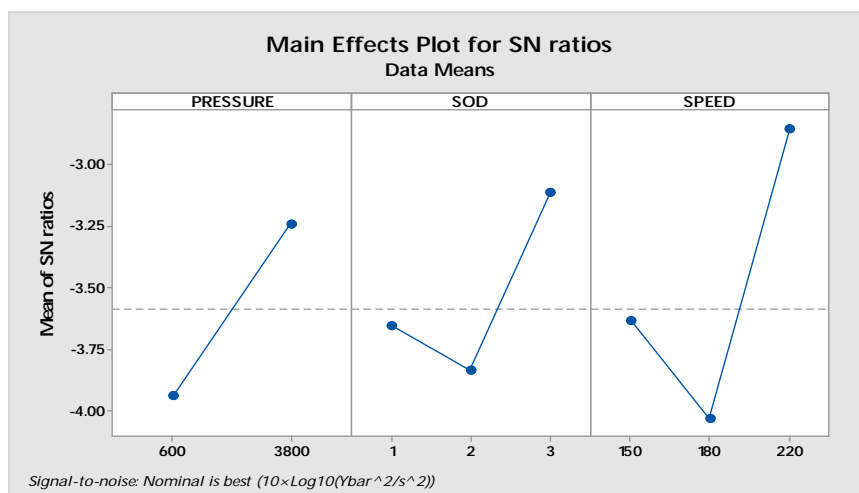


Fig 1.4 Main effects plot for S/N Ratio

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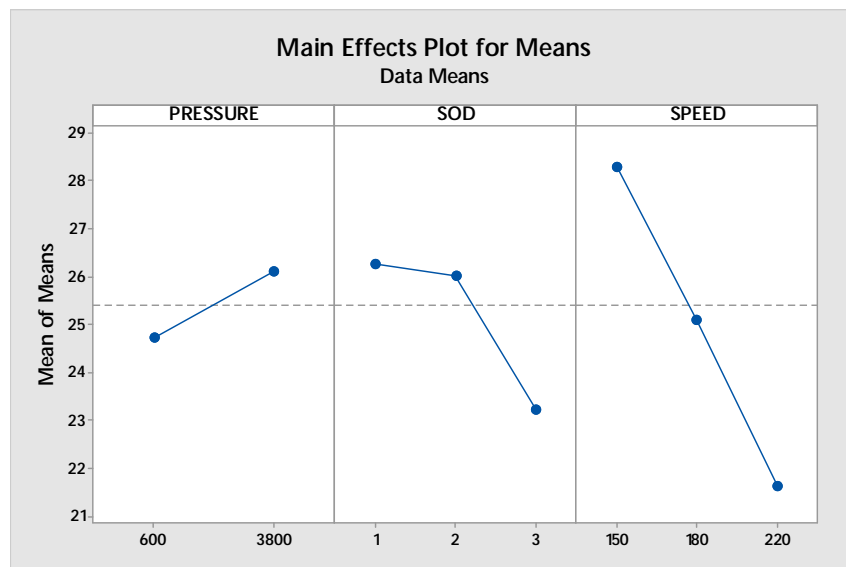


Fig 1.4 Main effects plot for Means

Taguchi Analysis:

MACHINING TIME, MRR, Kerf width versus PRESSURE, SOD, SPEED

Nominal is best ($10 \times \text{Log}_{10}(\bar{Y}^2/s^2)$)

Table 1.6 Response Table for Signal to Noise Ratios

| Level | PRESSURE | SOD | SPEED |
|-------|----------|--------|--------|
| 1 | -3.937 | -3.655 | -3.633 |
| 2 | -3.238 | -3.837 | -4.033 |
| 3 | -3.112 | -2.849 | - |
| Delta | 0.699 | 0.725 | 1.184 |
| Rank | 3 | 2 | 1 |

Table 1.7 Response Table for Means

| Level | PRESSURE | SOD | SPEED |
|-------|----------|-------|-------|
| 1 | 24.72 | 26.27 | 28.27 |
| 2 | 26.11 | 26.01 | 25.08 |
| 3 | 23.23 | 21.62 | - |
| Delta | 1.39 | 3.04 | 6.65 |
| Rank | 3 | 2 | 1 |

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5.2 Grey Relational Analysis

Table 1.8 Grey Relational Analysis

| Input Control Parameters | | | | Output responses | | | | S/N ratio | | Normalizing Sequence | | Deviation Sequence | | Grey Relational Coefficient | | Grey Relational Grade |
|--------------------------|----------|--------------------|-------|------------------|-----------------------|------------|-----------------------|------------|-----------------------|----------------------|-----------------------|--------------------|-----------------------|-----------------------------|--|-----------------------|
| Runs | Pressure | Stand Off Distance | Speed | Flank wear | Material Removal Rate | Kerf Width | Material Removal Rate | Flank wear | Material Removal Rate | Flank wear | Material Removal Rate | Flank wear | Material Removal Rate | | | |
| 1 | 600 | 1 | 150 | 0.020 | 1.48 | 1.514 | 1.988 | 0.435 | 0.000 | 0.565 | 1.000 | 0.470 | 0.333 | 0.402 | | |
| 2 | 600 | 3 | 180 | 0.023 | 2.57 | 1.563 | 2.320 | 0.089 | 0.044 | 0.911 | 0.956 | 0.354 | 0.343 | 0.349 | | |
| 3 | 600 | 2 | 180 | 0.045 | 3.45 | 1.576 | 2.913 | 0.000 | 0.122 | 1.000 | 0.878 | 0.333 | 0.363 | 0.348 | | |
| 4 | 600 | 1 | 220 | 0.079 | 3.93 | 1.564 | 4.181 | 0.084 | 0.288 | 0.916 | 0.712 | 0.353 | 0.413 | 0.383 | | |
| 5 | 3800 | 2 | 180 | 0.086 | 2.44 | 1.530 | 2.329 | 0.323 | 0.045 | 0.677 | 0.955 | 0.425 | 0.344 | 0.384 | | |
| 6 | 3800 | 1 | 150 | 0.068 | 3.87 | 1.534 | 8.169 | 0.299 | 0.813 | 0.701 | 0.187 | 0.416 | 0.728 | 0.572 | | |
| 7 | 3800 | 2 | 150 | 0.126 | 2.46 | 1.527 | 6.20 | 0.343 | 0.554 | 0.657 | 0.446 | 0.432 | 0.529 | 0.480 | | |
| 8 | 3800 | 3 | 220 | 0.067 | 2.34 | 1.472 | 2.990 | 0.733 | 0.132 | 0.267 | 0.868 | 0.652 | 0.365 | 0.509 | | |
| 9 | 3800 | 3 | 220 | 0.144 | 5.71 | 1.435 | 9.590 | 1.000 | 1.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 | | |

Table 1.8 Response Table for Grey Relational Grade

| Factors | Level 1 | Level 2 | Level 3 | Max - Min |
|--------------------|---------|---------|---------|-----------|
| Pressure | 0.366 | 0.446 | 0.663 | 0.297 |
| Stand Off Distance | 0.422 | 0.414 | 0.640 | 0.226 |
| Speed | 0.494 | 0.577 | 0.404 | 0.173 |

Table 1.9 Contribution table

| Factors | DoF | SS | MS | F Value | P Value | % Contribution |
|--------------------|-----|--------|--------|---------|---------|----------------|
| Pressure | 2 | 0.1415 | 0.0708 | 2.698 | - | 41.89% |
| Stand Off Distance | 2 | 0.0989 | 0.0495 | 1.886 | - | 29.28% |
| Speed | 2 | 0.0449 | 0.0225 | 0.856 | - | 13.30% |
| Error | 2 | 0.0525 | 0.0262 | - | - | 15.53% |
| Total | 8 | 0.3378 | 0.0422 | - | - | 100.00% |

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5.3 Main Effects Plot For Grey relational Grade

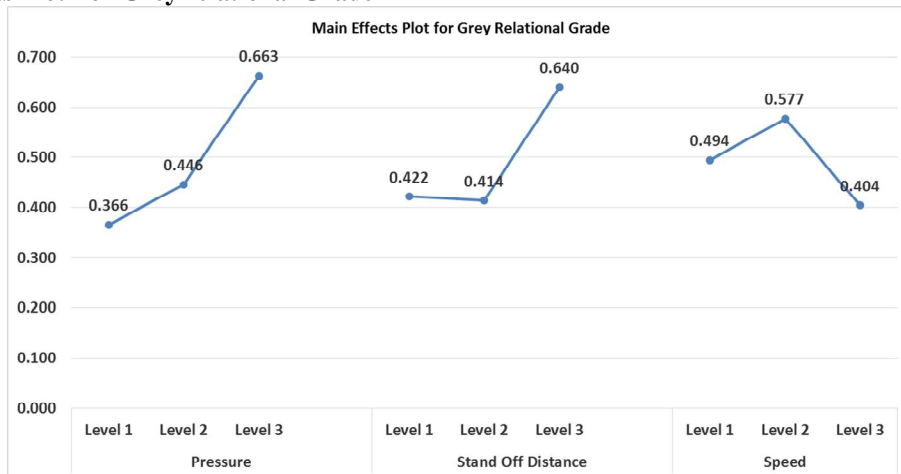
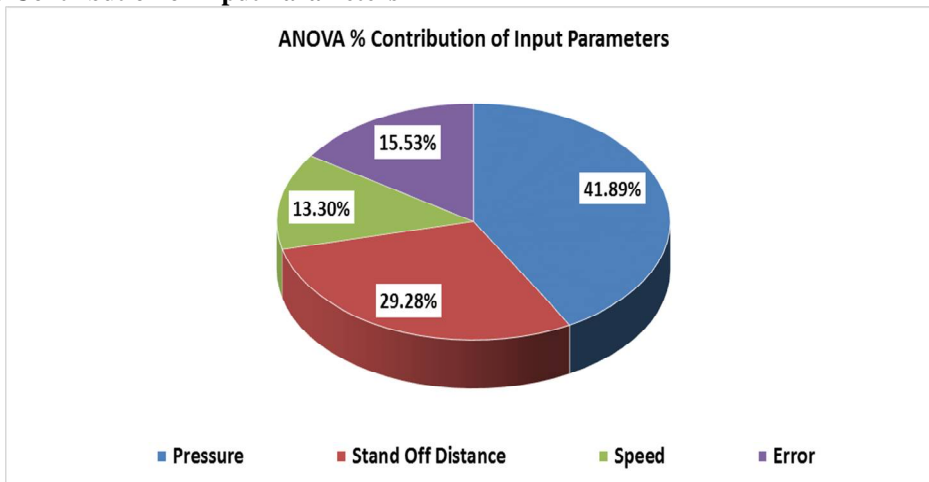


Fig.1.5 Main Effects Plot For Grey relational Grade

From the above graph(Fig.1.5) between Grey relational Grade and Level of Parameters, the GRG for level3 in Pressure is greater when compared with other levels. Similarly the GRG for level3 in Stand off Distance and level 2 in Speed is greater.

5.4 ANOVA % Contribution of Input Parameters



The contribution of Pressure is dominated when compared with other parameters like Standoff distance, Speed and Percentage of Error.

VI. CONCLUSION

The following conclusions can be drawn for effective machining of Stainless steel 410 by AWJM process as follows: Pressure is the most significant factor on MRR during AWJM. Because Pressure plays a major contribution from the analysis. At 600 bar pressure, The materials was not removed even by varying the cutting speed and Stand off distance, at 3800 bar pressure the material was removed, and the material removal rate was varying according to the cutting speed and the stand of Distance.

Main effects of MRR of each factor for various level conditions are calculated. According to calculation the MRR

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increases with three major parameter Pressure, Stand off distance, Cutting speed,. After optimization MRR is maximum in the case of pressure at 3800 bar, in the case of SOD at 3mm, and in the case of Cutting speed at the 180m/sec

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