An Experimental Investigation on Strain-Hardened Monel 400 using Abrasive Water Jet Machining

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Abstract - **This work deals with the study of Abrasive Water Jet Machining which has a major role in easily machining various materials including hard to machine materials. Here, Monel 400 was studied using AWJM. Initially the workpiece was hardened using one of the strain hardening method. After the hardening process the workpiece was subjected to machining process by varying Abrasive flow rate (gm/min), Traverse speed (mm/min), Stand-Off Distance (mm). The values to be input to perform the machining process were obtained with the help of L9 Orthogonal Array using Taguchi. In this study the effect of process parameters on MRR, Surface Roughness and Kerf Width were studied with the help of Grey Relational Analysis and the contributions were identified with the help of ANOVA. Finally the experimental results of the normal Monel 400 were compared with the Strain hardened Monel 400. It was observed that traverse speed greatly influenced Material Removal Rate and Surface roughness. Kerf width was greatly influenced by Abrasive flow Rate. It was noticed that MRR, Surface Roughness and the Kerf Width were lowered in case of hardened Monel 400.**

Keywords: Abrasive Flow Rate, Stand Off distance, Material Removal Rate, Kerf Width, Surface Roughness, traverse speed

I. INTRODUCTION

Swiftness in process with less ill effect on the materials being processed is one of the greatness concerns in today's world. Abrasive Water jet Machining (AWJM) is a type of non-conventional machining process which meets the above said desire to greater extent. In AWJM, the mechanical energy of the water and abrasives are used to achieve material removal or machining, here a pressure pump generates a stream of water with pressure rated up to 3500 bar. The pressure is converted to velocity via a tiny jewel orifice, creating a stream as small as human hair which can cut soft materials. To increase the cutting power by 1000 times, abrasive grains are pulled into the supersonic waterjet stream. Water and the abrasive grains(garnet) exit the cutting head nearly four times the speed of sound, capable of cutting steel over one foot thick. The cutting ability of water jet machining can be improved drastically by adding hard and sharp abrasive particles into the water jet. The domain of "harder and "difficult-to machine" materials like thick plates of steels, aluminium and other commercial materials, metal matrix and ceramic matrix composites, reinforced plastics, layered composites etc. are reserved for AWJM [1]..

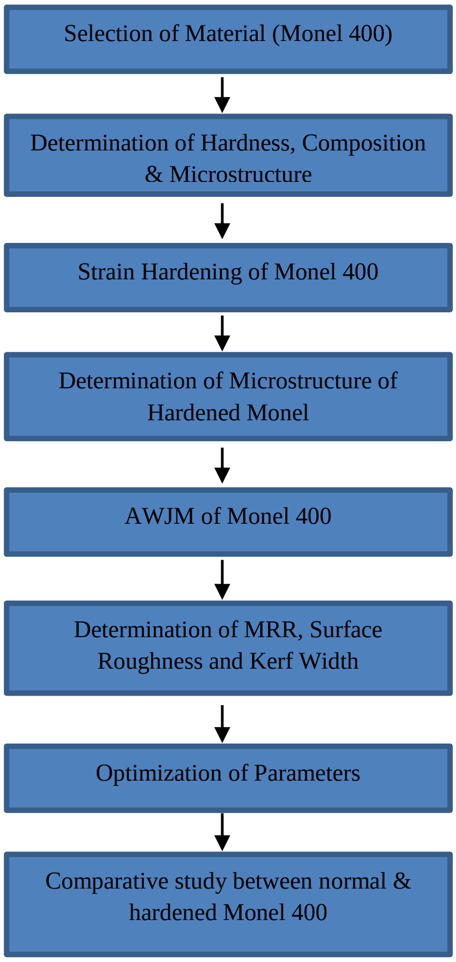
The width of cut increases as the SOD increases.[2] It was observed that the width of cut was very small for garnet abrasive followed by aluminum oxide and silicon carbide. It was observed the width of cut reduces with the increase in feed rate. The width of cut was found to increase with the increase in pressure. Finally by observation it is seen that garnet would be better in use against Monel 400. The kerf characteristics in AWJM of marble were three different parameters (Nozzle pressure, Traverse speed, Abrasive flow rate) are considered for investigation following which optimization was carried out using Taguchi DOE and ANOVA which determined each's contributions and Traverse speed was found to be the most contributing factor for taper angle and top kerf width as studied. [3] The study of the influence of the process parameters on the Surface Roughness and the topography for process enhancement [4] about the method that can be adopted to improve the machinability of the materials herein observation was seen that the Abrasive flow rate and the Stand-Off Distance had the more significant role in determining the surface quality. These details helped in determination of parameters to be considered in determining MRR, Surface Roughness and Kerf Width. The effect of the cutting speed on the Surface Roughness in abrasive water jet cutting of the 10 mm stainless steel plate was studied by [5]. Surface Roughness was measured in various locations across the cut. Differences between the obtained geometric structure and measured roughness parameter values were presented.

The effects of cutting parameters are determined [6]. Further the effect of thermal treatment on surface morphology of the material machined has been studied for analysing the effectiveness of the present methodology. The grit embedment can be minimized by machining with a high jet traverse speed [7]. The levels of grit embedment and development of surface morphology was observed to depend upon complex interactions of the various processing parameters, and a rationale for the observed behaviour was finally proposed.

An experimental investigation of the process parameters on the AWJM process which is characterized by a number of process parameters that affects the quality of machining was done [8] In this work, the influence of three parameters, namely pressure, traverse rate and stand-off distance on surface finish. The Full factorial experimental design was applied for experimentation. Then analysis of variance was performed and an empirical model was developed by multilinear regression analysis for surface roughness.

The influence of the process parameters of the AWJM on surface roughness and optimization using Taguchi method and ANOVA was performed [9]. It was found that the abrasive materials, hydraulic pressure, Stand-Off Distance and the traverse speed were the significant control factors and the cutting orientation was one of the insignificant control factors in controlling the Surface Roughness. It is confirmed that the determined optimum combination of AWJM parameters satisfy the real need for machining. The study about the impact of machining parameters on the Material Removal Rate and the Surface Roughness and optimization using Taguchi method, Analysis of Variance and Signal to Noise ratio was done [10] in order to predict optimal choice for each AWJM parameters such as Traverse speed, Abrasive Flow Rate and SOD. The adopted methods for the optimization are applied. Experiments were conducted in varying water pressure, nozzle traverse speed, abrasive mass flow rate and standoff distance. The effects of these parameters on depth of cut and surface roughness were studied based on the experimental results. In order to correctly select the process parameters, an empirical model for the prediction of depth of cut in abrasive waterjet cutting of stainless steel was developed using regression analysis [11]. This developed model has been verified with the experimental results and reveals a high applicability of the model within the experimental range used.

II. THE PROCESS FLOWCHART



III. STRAIN HARDENING OF MONEL 400

Work hardening also known as strain hardening or cold working, is the strengthening of a metal by plastic deformation. This strengthening occurs because of dislocation movements and dislocation generation within the crystal structure of the material. Many non-brittle metals with a reasonably high melting point as well as several polymers can be strengthened in this fashion. Alloys not amenable to heat treatment, including low-carbon steel, are often work-hardened. Some materials cannot be work-hardened at low temperatures, such as indium; however others can only be strengthened via work hardening, such as pure copper and aluminium.

Work hardening may be desirable or undesirable depending on the context. An example of undesirable work hardening is during machining when early passes of a cutter inadvertently work-harden the work piece surface, causing damage to the cutter during the later passes. Certain alloys are more prone to this than others; super alloys such as Inconel require machining strategies that take it into account. An example of desirable work hardening is that which occurs in metalworking processes that intentionally induce plastic deformation to exact a shape change. These processes are known as cold working or cold forming processes. They are characterized

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 05, May - 2017

by shaping the work piece at a temperature below its recrystallization temperature, usually at ambient temperature. Cold forming techniques are usually classified into four major groups: squeezing, bending, drawing, and shearing. Applications include the heading of bolts and cap screws and the finishing of cold rolled steel. In cold forming, metal is formed at high speed and high pressure using tool steel or carbide dies. The cold working of the metal increases the hardness, yield strength, and tensile strength.

In metalworking, rolling is a metal forming process in which metal stock is passed through one or more pairs of rolls to reduce the thickness and to make the thickness uniform. The concept is similar to the rolling of dough. Rolling is classified according to the temperature of the metal rolled. If the temperature of the metal is above its recrystallization temperature, then the process is known as hot rolling. If the temperature of the metal is below its recrystallization temperature, the process is known as cold rolling. In terms of usage, hot rolling processes more tonnage than any other manufacturing process, and cold rolling processes the most tonnage out of all cold working processes. Roll stands holding pairs of rolls are grouped together into rolling mills that can quickly process metal, typically steel, into products such as structural steel (I-beams, angle stock, channel stock, and so on), bar stock, and rails. Most steel mills have rolling mill divisions that convert the semi-finished casting products into finished products.

In the present study the work piece is passed through the rollers and the thickness was reduced from 6mm to 3.2mm. This lead to the increase in hardness of work piece from 81 to 91 units when observed on the HRB scale.

IV. MACHINING AND MEASUREMENT

The main aim in performing this machining process is to determine the effects of process parameters on the Monel 400 and to determine the optimized value which would provide a better combination of output. First the workpiece was purchased. The combinations of input parameters were decided using Taguchi design (L9 Orthogonal Array). Then the workpiece was hardened using strain hardening process in order to facilitate its usage in wide range of applications. Then the hardened Monel 400 was fixed in Abrasive Water Jet machine bed using fixture. Then the programmed machine made the cut on the workpiece with respect to the instructions provided, as shown below in Fig.IV.1.

Fig.IV.2 Machined work piece

Fig.IV.3 AWJM setup

The VMM was used to measure the kerf width of the cuts. First the top kerf width was measured by taking three trials. The same was repeated for the bottom Kerf width. Then the average of the kerf width was calculated and was noted down. The pictorial representation of the machine is given below

Fig.IV.3 Video Measuring Machine

Then the Surface Roughness is measured using Profilometer. The pictorial representation of the instrument is given below.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 05, May - 2017

Fig.IV.4 Profilometer

V. OPTIMIZATION OF PARAMETERS

The preliminary test results of the Monel400 subjected to strain hardening showed reduction in Surface roughness and Kerf width than the normal Monel. Thus it is proposed to optimize the strain hardened Monel400 in order to obtain enhancement in its properties. The Grey relational technique is adopted in this study to study the effect of Abrasive Flow Rate, Traverse speed, Stand-Off Distance.

A) DOE using Taguchi Method

The Taguchi parameter design is a powerful and efficient method for optimizing the quality performance of manufacturing processes. The Taguchi method is used for achieving high quality targets without increasing the cost. This effective method utilizes the orthogonal Array (OA) from the experimental design to study more variables with less number of experiments. The conclusions drawn from the small-scale experiments are valid the entire experimental range, spanned by the control factors and their level settings. The method uses, spanned by the control factors and their level settings. The method uses the statistical measure of performance signal-to noise ratio(S/N), which is the logarithmic function of the desired output, to serve as the objective function for optimization.

a) Orthogonal Array for Experimentation

The number of factors influencing the optimizing function, and the number of levels to be considered for the factors are required, to select the appropriate orthogonal array for experimentation. To select an appropriate orthogonal array for the experiments, the total degrees of freedom need to be computed. The three parameters or factors of the AWJM identified are the Abrasive Flow Rate, Traverse Speed, Stand-Off Distance. In the present investigation, the L9(3)3 orthogonal array is chosen. In the Orthogonal array, the first column is assigned to the Abrasive Flow Rate, the second column to the Traverse Speed, the third column to the Stand-Off Distance.

b) Level for the Factors

The factors and the levels for the Abrasive Water Jet Machining of Monel400 are selected based on the published literature and preliminary study. The level of factors considered were chosen for DOE as shown below

Table.V.1 Level for the Factors

Factors	L 1	L2	L3
Abrasive Flow Rate	250	300	350
Traverse Speed	100	120	140
Stand-Odd Distance	1	2	3

c) Assessment of Performance

The response to be studied are the Material Removal Rate (the higher the better), Surface roughness (lower the better), and Kerf Width (lower the better). The quality performance of the hardened Monel400 sample was evaluated based on the L9 Orthogonal Array was evaluated by determining MRR, Surface Roughness and Kerf Width. The Surface Roughness was calculated using surface Roughness measuring instrument, the Kerf width was calculated by calculating the top width and the bottom width and by taking its average. The measured values of MRR, Surface Roughness and Kerf Width are shown below.

Table.V.2. Level for the Factors

Exp. No	Material Removal Rate(mm^3/min)	Surface Roughness(μm)	Kerf Width(mm)
1	243.680	3.79	0.7615
2	293.568	3.26	0.7645
3	347.424	3.51	0.7755
4	242.400	3.06	0.7575
5	294.720	3.83	0.7675
6	331.744	3.90	0.7405
7	235.840	3.51	0.7370
8	264.576	3.75	0.6890
9	257.376	3.97	0.5745

B) Grey Relational Analysis

The GRA, based on the grey system theory can be used, for solving the complicated interrelationships among the multi responses (Deng 1982). In the present study, the multi-response process on the basis of GRA, is incorporated into the Taguchi method, to decide the optimum combination of the level of factors and optimize the AWJM process. It is a case of multi-response optimization, which is different from a single response optimization, in which only one parameter may be considered for optimization. The higher S/N ratio for one performance characteristics may correspond to lower S/N ratio for another. Therefore, the overall estimation of S/N ratio is necessary for the optimization of the multiple performance characteristics. In the GRA, the experimental data are first normalized to a range from zero to one, known as Grey relational generation. The next step is the grey relational coefficient, which is based on the normalized experimental data to represent the relationship between the desired and actual experimental data. The grey relational grade is calculated by averaging the grey relational coefficient corresponding to the selected responses. The calculated grey relational grade is a measure of the overall performance characteristic of the multiple response process. The optimization problem results in changing the multiple responses into the optimization of a single response, by utilizing the function of the grey relational grade. The optimized levels of the factors are the

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 05, May - 2017

respective levels at which the maximum overall grey relational grade is attained.

a) Signal-To-Noise Ratio for the responses

The response values from the three replicates were transformed into S?N ratios. The S/N ratio is based on the lower- the-better or higher-the-better conditions encountered in the analysis. The output parameters selected in the study for the process of evaluating the Monel400 are MRR (should be higher-the-better), Surface Roughness (should be lower-the-better) and Kerf Width (should be lower-the-better). The expressions to calculate the S/N ratio are given below with the help of model calculation.

Material Removal Rate (Higher-the-better)

$$\text{S/N ratio}= -10\log_{10}\left[\left(\frac{1}{r}\right)\sum_{i=1}^{r}\frac{1}{y_{ij}^{2}}\right]$$

Surface Roughness (lower-the-better)

$$\text{S/N ratio}= -10\log_{10}\left[\left(\frac{1}{r}\right)\sum_{i=1}^{r}y_{ij}^{2}\right]$$

Kerf Width (lower-the-better)

$$\text{S/N ratio}= -10\log_{10}\left[\left(\frac{1}{r}\right)\sum_{i=1}^{r}y_{ij}^{2}\right]$$

Where, r = number of replications, y_{ij} =the observed response value,

i =1, 2…….r, j = 1, 2….n, n = number of experiments.

The model calculations are performed below.

- Material Removal Rate(Higher-the-better)

$$\text{S/N ratio} = -10\log_{10}\left[\left(\frac{1}{1}\right)\left[\frac{1}{293.568^{2}}\right]\right]$$

= 49.354

- Surface Roughness(Lower-the-better)

$$\text{S/N ratio} = -10\log_{10}\left[\left(\frac{1}{1}\right)[3.26^{2}]\right]$$

= -10.264

- Kerf Width(Lower-the-better)

$$\text{S/N ratio} = -10\log_{10}\left[\left(\frac{1}{1}\right)[0.7645^{2}]\right]$$

= 2.332

Table.V.3 S/N ratios of Monel 400

Exp. No	Material Removal Rate	Surface Roughness	Kerf Width
1	47.736	-11.573	2.366
2	49.354	-10.264	2.332
3	50.817	-10.906	2.208
4	47.691	-9.714	2.412
5	49.388	-11.664	2.298
6	50.416	-11.821	2.609
7	47.452	-10.906	2.651
8	48.451	-11.481	3.236
9	48.211	-11.976	4.814

b) Data pre-processing

Data pre-processing is a process of transferring the original sequence to a comparable sequence. Depending on the characteristics of the data sequence, there are various methodologies of data pre-processing available for the grey relational analysis. In the grey relational analysis, a data pre-processing is first performed, in order to normalize the raw data for analysis. Normalization is a transformation performed on a single data input, to distribute the data evenly and scale it into an acceptable range for further analysis (Deng 1990; 1992). The S/N ratio value is adopted when normalizing the data in the grey relational analysis. Thus, the data sequence of the MRR should be in the type of the higher- the- better criterion and can be expressed as,

$$Z_{ij}=\frac{y_{ij}-\min(y_{ij}, i=1,2\ldots..n)}{\max(y_{ij}, i=1,2\ldots\ldots n)-\min(y_{ij}, i=1,2\ldots..n)}$$

Similarly, the Surface Roughness and Kerf width should be in the type of the lower-the-better criterion, and can be expressed as,

$$Z_{ij}=\frac{\max(y_{ij,}i=1,2\ldots..n)-y_{ij}}{\max(y_{ij}, i=1,2\ldots..n)-\min(y_{ij}, i=1,2\ldots..n)}$$

Where, Z_{ij} = normalized S/N ratio values; where i =1, 2…....n; j = 1, 2...k;

n = number of experimental data items,

k = number of responses.

The model calculations are performed below.

- Material Removal Rate(Higher-the-better)

$$Z_{ij}=\frac{49.354-47.452}{50.817-47.452}$$

=0.5652

- Surface Roughness(Lower-the-better)

$$Z_{ij}=\frac{-9.714-(-10.264)}{-9.714-(-11.976)}$$

=0.2430

- Kerf Width(Lower-the-better)

$$Z_{ij} = \frac{4.814-2.332}{4.814-2.208}$$

$$=0.9520$$

Table.V.4 Normalized S/N ratios for Monel 400

Exp. No	Material Removal Rate(mm^3/min)	Surface Roughness (μm)	Kerf Width(mm)
1	0.084	0.822	0.939
2	0.565	0.243	0.952
3	1	0.527	1
4	0.071	0	0.922
5	0.575	0862	0.965
6	0.881	0.931	0.846
7	0	0.527	0.830
8	0.297	0.781	0.606
9	0.225	1	0

c) *Grey Relational Coefficient*

In the grey relational analysis, the measure of the relevancy between two systems or two sequences is defined as the grey relational grade. After the data pre-processing, a grey relational coefficient can be calculated using the pre-processed sequences. The grey relational coefficient is calculated to express the relationship between the ideal (best) and the actual normalized experimental results. The grey relational coefficient can be expressed as,

$$\gamma(y_{\circ}(K),y_j(K)) = \frac{\Delta min+\zeta\Delta max}{\Delta_{\circ j}(K)+\zeta\Delta max}$$

Where,

j = 1, 2...n; k = 1, 2...m;

n is the number of experimental data items and m is the number of response

$y_{\circ}(k)$ is the reference sequence ($y_{\circ}(k)$ = 1, k = 1,2...m);

$y_i(k)$ is the specific comparison sequence;

$\Delta_{\circ j}(K) = \|y_{\circ}(K) - y_j(K)\|$ = The absolute value of the difference between $y_{\circ}(K)$ and $y_i(K)$;

Δmin = Smallest value of $y_j(K)$;

Δmax = Largest value of $y_j(K)$;

ζ is the distinguishing coefficient set between zero and one; in our case study, the process parameters have equal weighting, and it was set to = 0.5.

The model calculation is performed below

- Material Removal Rate

$$\Delta_{\circ j}(K) = 1 - 0.565$$

$$= 0.435$$

$$\gamma(y_{\circ}(K),y_j(K)) = \frac{0+0.5}{0.435+0.5}$$

$$=0.535$$

- Surface Roughness

$$\Delta_{\circ j}(K) = 1 - 0.243$$

$$= 0.757$$

$$\gamma(y_{\circ}(K),y_j(K)) = \frac{0+0.5}{0.757+0.5}$$

$$= 0.398$$

- Kerf Width

$$\Delta_{\circ j}(K) = 1 - 0.952$$

$$= 0.048$$

$$\gamma(y_{\circ}(K),y_j(K)) = \frac{0+0.5}{0.048+0.5}$$

$$= 0.912$$

d) *Grey Relational Grades*

Each response of the grey relational coefficients is transformed into the grey relational grade. On the basis of the grey relational grade, the factor effects are estimated and the grades are considered as the optimized level for each controllable factor of the deep cryogenic treatment process. The grey relational grade can be expressed as,

$$\bar{\gamma}_j = \frac{1}{K}\sum_{1=1}^{m}\gamma_{ij}$$

Where, $\bar{\gamma}_j$ is the grey relational grade for the jth experiment and k is the number of performance characteristics.

The model calculation is performed below.

$$\bar{\gamma}_j = \frac{1}{3}[0.535 + 0.398 + 0.912]$$

$$=0.615$$

Table.V.5 Grey relational coefficient and Grey relational grade for Monel 400

Exp. No	Grey Relational Coefficient			Grey relational grade
	Material Removal Rate	Surface Roughness	Kerf Width	
1	0.353	0.737	0.891	0.660
2	0.535	0.398	0.912	0.615
3	1	0.514	1	0.838
4	0.349	0.333	0.865	0.516
5	0.541	0.784	0.935	0.753
6	0.807	0.879	0.765	0.817
7	0.333	0.514	0.746	0.531
8	0.416	0.695	0.559	0.556
9	0.392	1	0.333	0.575

From the grey relational grade shown, it is seen that experiment three has the best multiple response among the nine experiments for Monel400, because it has the highest grey relational grade of 0.838. A higher grey relational grade implies better performance; therefore, on the basis of the grey relational grade, the effect of factors can be estimated, and the optimum level for each controllable factor is determined.

e) Best Experimental Run

In order to determine the average grey relational grade for each factor level, the response table of the Taguchi method is to be evolved as explained below. First, the grey relational grade is grouped by the factor level for each column in the OA, and then they are averaged. Typically the response value of level L1 of the Material Removal Rate is the average of the grey relation grade of the experiments in which level L1 is considered for the Material Removal Rate. This could be done meticulously by referring the Orthogonal Array. Model calculation to evolve the entries in the response table for the grey relational grade is shown below. The highest response value indicates that the Respective level is the optimum for the considered factor in order to get the best multi response characteristic for the process. The collection of all highest response values for all the factors defines the optimized Abrasive Water Jet Machining. In other words it is the process which gives the optimized combination of Material Removal Rate, Surface Roughness and Kerf Width which improves the product usage.

The model calculations are performed below.

- Abrasive Flow Rate(Experiment No: 1, 2, 3)

  $L1 = \frac{1}{3}(0.66 + 0.615 + 0.838)$

  $= 0.704$

- Traverse Speed(Experiment No: 1, 4, 7)

  $L1 = \frac{1}{3}(0.66 + 0.516 + 0.531)$

  $= 0.569$

- Stand-Off Distance(Experiment No: 1, 6, 8)

  $L1 = \frac{1}{2}(0.66 + 0.817 + 0.556)$

  $= 0.677$

Table.V.6 Response table for overall grey relational grade

Level	Abrasive Flow Rate	Traverse Speed	Stand-Off Distance
L1	0.704	0.569	0.677
L2	0.695	0.641	0.568
L3	0.554	0.743	0.707

Thus the level 1 for Abrasive Flow Rate, level 3 for Traverse Speed and level 3 for Stand-Off Distance are the values selected for the AWJM parameters. Based on the above study, the optimized values for the Abrasive Water Jet Machining of the Monel400 are Abrasive Flow Rate of 250(gm/min), Traverse Speed of 140(mm/min) and Stand-Off Distance of 3(mm).

C) RESPONSE TABLES

This is performed in order to determine the parameter which is having the more influence on the output response. For this the Grey relational coefficients of the MRR, Surface Roughness and Kerf Width corresponding to the different levels are summed up and then averaged. The results for each levels are finally plotted in the form of table. Now the difference between the higher and the lower values of the level are determined.

a) Response Table for MRR

Table.V.7 Response table for MRR

Level	L1	L2	L3	Difference
Abrasive flow Rate	0.629	0.566	0.380	0.249
Traverse speed	0.345	0.497	0.733	0.388
SOD	0.525	0.425	0.625	0.2

It is observed that the difference value of the Traverse speed is greater than the difference value of the Abrasive Flow Rate and Stand-Off Distance. Thus it is concluded that Traverse speed has the greater effect on deciding the Material Removal Rate and the Stand –Off Distance has the lower effect on deciding the Material Removal Rate.

b) Response Table for Surface Roughness

Table.V.8 Response table for Surface Roughness

Level	L1	L2	L3	Difference
Abrasive Flow Rate	0.549	0.665	0.736	0.187
Traverse Speed	0.528	0.626	0.798	0.27
SOD	0.770	0.577	0.604	0.193

It is observed that the difference value of the Traverse speed is greater than the difference value of the Abrasive Flow Rate and Stand-Off Distance. Thus it is concluded that Traverse speed has the greater effect on deciding the Surface Roughness and the Abrasive Flow Rate has the lower effect on deciding the Surface Roughness.

c) Response Table for Kerf Width

Table.V.9 Response table for Kerf Width

Level	L1	L2	L3	Difference
Abrasive Flow Rate	0.934	0.855	0.546	0.388
Traverse Speed	0.834	0.802	0.699	0.135
SOD	0.738	0.703	0.893	0.19

It is observed that the difference value of the Abrasive Flow Rate is greater than the difference value of the Traverse speed and Stand-Off Distance. Thus it is concluded that Abrasive Flow Rate has the greater effect on deciding the Kerf Width and the Traverse speed has the lower effect on deciding the Kerf Width.

D) ANOVA

The goal of the ANOVA in this present study, is to investigate the significance of each input parameter influencing the characteristics namely Material Removal Rate, Surface Roughness, Kerf Width of the Monel400. This is accomplished by translating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into the contributions by each parameter and the error as explained below. The sample calculation for factor A to determine the total sum of squares, sum of squares, mean sum of squares and % contribution is shown below. The expression for each step below is discussed in section below.

- Degree of Freedom(DOF)
  DOF for factor= Number of levels-1
- Correction Factor(CF)

$$=\frac{1}{m}\left[\sum_{i=1}^{m} y_i\right]^2$$

- Total sum of square (SS_T)

$$=\sum_{i=1}^{m} y_i^2 - CF$$

- Sum of square deviations (SS_d)

$$=\frac{F_1^2+F_2^2+F_3^2}{3} - CF$$

- Mean Sum of square(MSS)

$$=\frac{Sum\ of\ square(SS_d)}{Degree\ of\ Freedom(DOF)}$$

- % Contribution

$$=\frac{Sum\ of\ square(SS_d)}{Total\ sum\ of\ square(SS_T)}$$

The model calculations are performed below.

- Degree Of Freedom
  (DOF)= Number of Levels-1
  = 3-1
  = 2
- Correction Factor(CF)

$$=\frac{1}{m}\left[\sum_{i=1}^{m} y_i\right]^2$$

$$=\frac{\begin{pmatrix}0.66+0.615+0.838+0.516+\\0.753+0.817+0.531+0.556+0.575\end{pmatrix}^2}{9}$$

=3.817

- Total sum of square (SS_T)

$$=\sum_{i=1}^{m} y_i^2 - CF$$

$$=0.66^2+0.615^2+0.838^2+0.516^2+0.753^2+0.817^2+0.531^2+0.556^2+0.575^2-CF$$

=0.122

- Sum of square deviations (SS_d)

$$=\frac{F_1^2+F_2^2+F_3^2}{3} - CF$$

F_1 for factor A= (0.660+0.615+0.838) = 2.113
F_2 for factor A= (0.516+0.753+0.817) = 2.086
F_3 for factor A= (0.531+0.556+0.575) = 1.662

$$=\frac{2.113^2+2.086^2+1.662^2}{3} - CF$$

= 0.042

- Mean Sum of square (MSS)

$$=\frac{Sum\ of\ square(SS_d)}{Degree\ of\ Freedom(DOF)}$$

$$\Rightarrow \frac{0.042}{2} = 0.021$$

- % Contribution

$$=\frac{Sum\ of\ square(SS_d)}{Total\ sum\ of\ square(SS_T)}$$

$$=\frac{0.042}{0.122}*100$$

= 34.4

Table.V.10 ANOVA table for grey relation grade

Factor	Parameter	DOF	SS_d	MSS	% Contribution
A	Abrasive Flow Rate	2	0.042	0.021	34.42
B	Traverse Speed	2	0.046	0.023	37.70
C	Stand-Off Distance	2	0.032	0.016	26.23
Error		2	0.002	0.001	1.65
Total		8	0.122		100

The above table shows the ANOVA Table for the grey relational grade. From the ANOVA, it is clear that the contribution of the input parameters, such as the Abrasive Flow Rate, Traverse Speed and Stand-Off Distance are 34.42%, 37.70%, 26.23 respectively. It is found that among the three factors, the Traverse Speed makes the major contribution, and has a significant effect on the multiple Response characteristics (MRR, Surface Roughness and Kerf Width) of Monel400. This suggests that the Traverse Speed is more important than the Abrasive Flow Rate and Stand-Off Distance for Monel400.

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a) ANOVA for Material Removal Rate

$$MRR = 178.88 - 0.423 \times \text{Abrasive flow rate (gm/min)} + 1.789 \times \text{Traverse speed(mm/min)} + 6.33 \times \text{SOD(mm)}$$

The regression formula derived from the ANOVA table can be used to calculate the Material Removal Rate by feeding the input values to the AWJM. The Material Removal Rate values were calculated and found to be within a 3% error of the measured values for the same inputs.

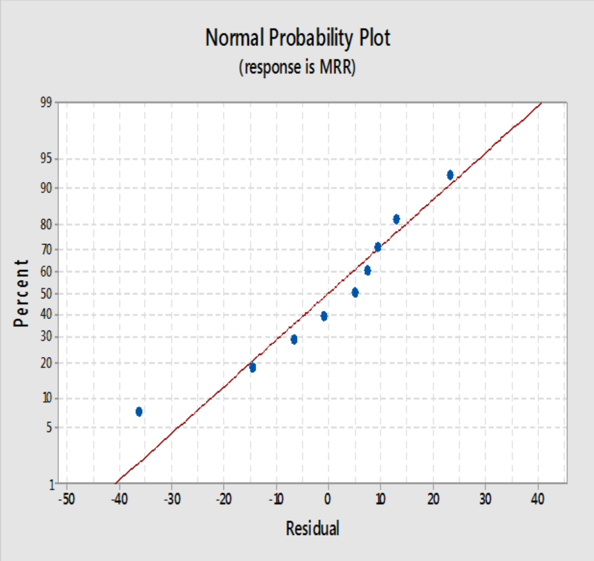

Fig. V.1 Normal plot of residual for MRR

The normal probability plot of the residuals (i.e. error = predicted value from model-actual value) for Material Removal Rate is shown above. The figure reveals that the residuals lie reasonably close to a straight line, giving support that the terms mentioned in the model are the significant ones.

b) ANOVA for Surface Roughness

Surface roughness= 2.13 + 0.00223 Abrasive flow rate (gm/min) + 0.00850 Traverse speed(mm/min) - 0.098 SOD(mm)

The regression formula derived from the ANOVA table can be used to calculate the Surface Roughness by feeding the input values to the AWJM. The Surface Roughness values were calculated and found to be within a 3% error of the measured values for the same inputs.

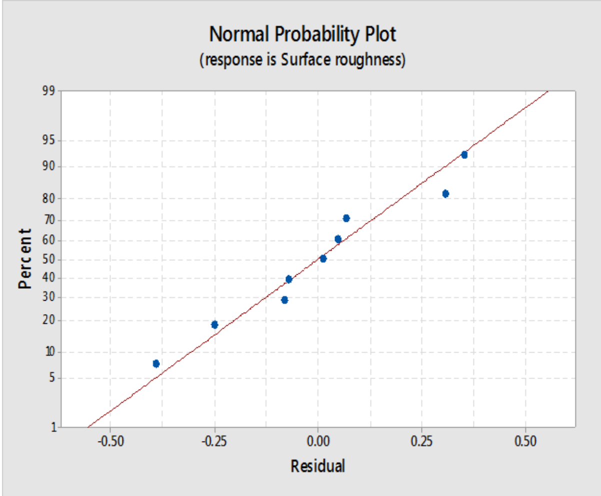

Fig.V.2 Normal plot of residual for Surface Roughness

The normal probability plot of the residuals (i.e. error = predicted value from model-actual value) for Surface Roughness is shown above. The figure reveals that the residuals lie reasonably close to a straight line, giving support that the terms mentioned in the model are the significant ones.

c) ANOVA for Kerf Width

Kerf Width = 1.167 - 0.001003 Abrasive flow rate (gm/min) - 0.001379 Traverse speed (mm/min) + 0.0148 SOD(mm)

The regression formula derived from the ANOVA table can be used to calculate the Kerf Width by feeding the input values to the AWJM. The Kerf Width values were calculated and found to be within a 3% error of the measured values for the same inputs.

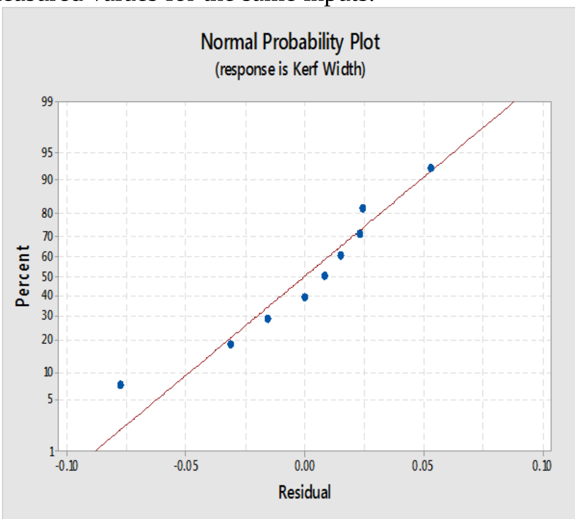

Fig.V.3 Normal plot of residual for Kerf Width

The normal probability plot of the residuals (i.e. error = predicted value from model-actual value) for Kerf Width is shown above. The figure reveals that the residuals lie reasonably close to a straight line, giving support that the terms mentioned in the model are the significant ones.

E) TAGUCHI PLOTS

The Taguchi plots are plotted in order to determine the optimum value for parameters to obtain a good response as per the requirements

a) Taguchi Plot for MRR

From the graph the optimum value for better Material Removal Rate can be inferred. It is found that for Abrasive flow Rate of 250(gm/min), Traverse speed of 140(mm/min) and Stand-Off Distance of 3(mm) better Material Removal Rate can be obtained.

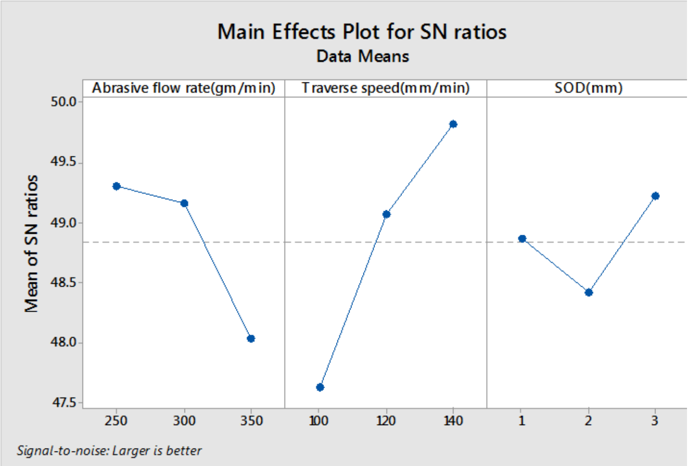

Fig.V.4 Taguchi plot for MRR

b) Taguchi Plot for Surface Finish

From the graph the optimum value for better Surface Finish can be inferred. It is found that for Abrasive flow Rate of 250(gm/min), Traverse speed of 100(mm/min) and Stand-Off Distance of 2(mm) better Surface Finish can be obtained.

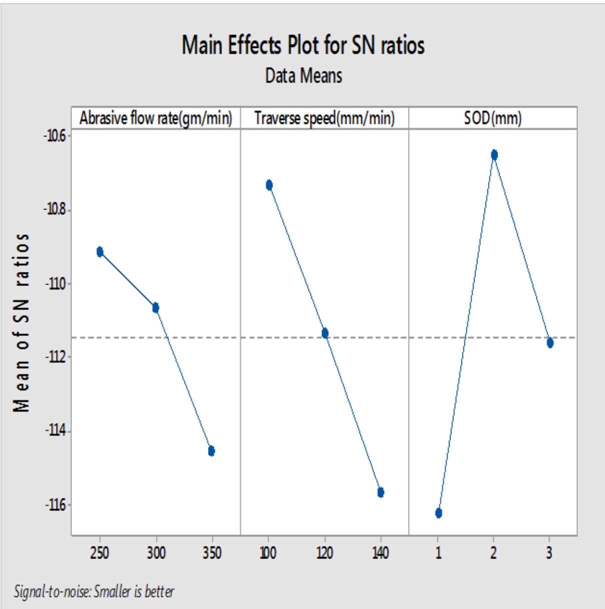

Fig.V.5 Taguchi plot for Surface Roughness

c) Taguchi Plot for Kerf Width

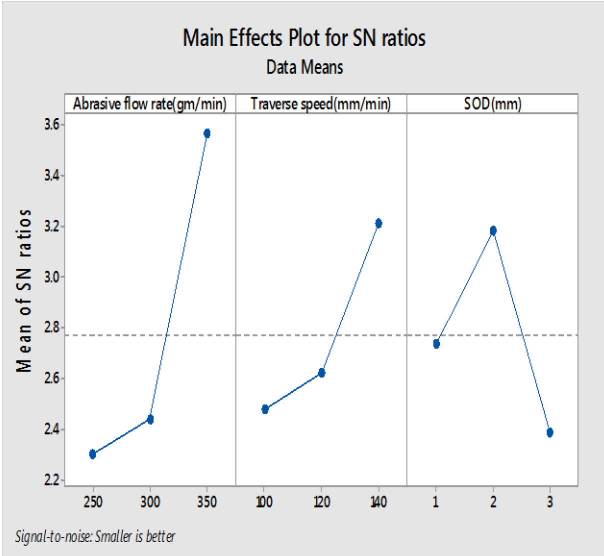

Fig.V.6 Taguchi plot for Kerf Width

From the graph the optimum value for lower Kerf Width can be inferred. It is found that for Abrasive flow Rate of 350(gm/min), Traverse speed of 140(mm/min) and Stand-Off Distance of 2(mm) lower Kerf Width can be obtained.

VI. COMPARATIVE STUDY

Here the study is dealt with the comparison of the normal Monel 400 with the Strain hardened Monel 400. Here the output for the two forms of Monel is taken for the same input parameters. The comparative study is performed for the both.

A) For Material Removal Rate

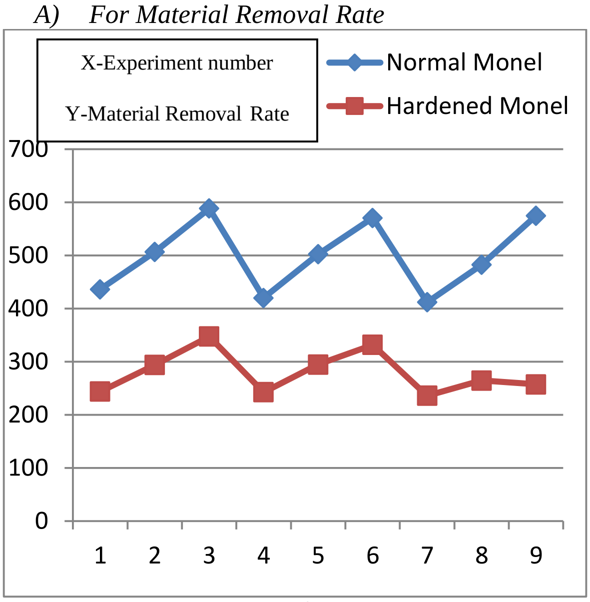

Fig.VI.1Comparative graph for Material Removal Rate

It is observed that the MRR for a normal Monel of lower hardness is higher than the MRR for strain hardened Monel. Thus MRR is reduced with increased hardness.

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B) For Surface Roughness

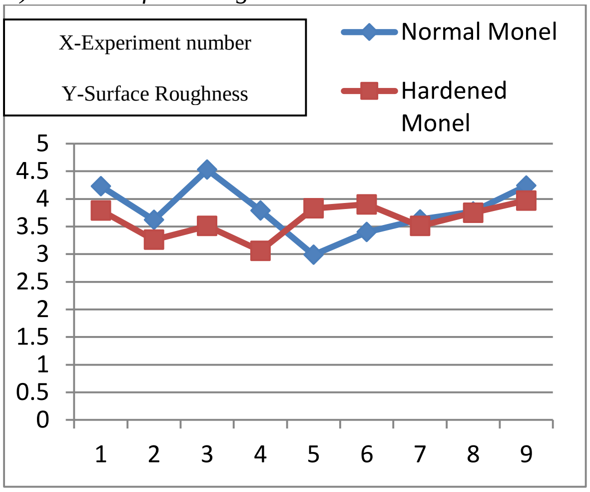

Fig.VI.2 Comparative graph for Surface Roughness

From figure.V.2 it is observed that the Surface roughness for the Hardened Monel is lower than the normal Monel. It is observed that at two points the surface roughness is higher for the Hardened Monel than the normal Monel. This might be due to some irregularity in measurement of may be due to some calibration error. Finally it is concluded that the surface roughness of the Monel 400 is decreased with increase in its hardness.

C) For Kerf Width

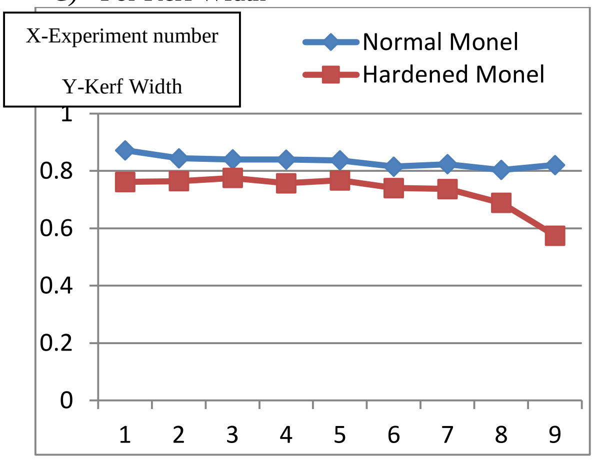

Fig.VI.3 Comparative graph for Kerf Width

From the above graph it is observed that the Kerf Width for the Hardened Monel 400 is lower than the Kerf Width of the normal Monel 400. Its acting true for all the input parameters. Thus it is concluded that with the increase in hardened the Kerf Width reduces.

Thus it is concluded that with the increase in hardness the MRR, Surface Roughness and Kerf Width decreases.

VII. CONCLUSION

This study presents the findings of an experimental investigation of the effect of Abrasive Flow Rate, Traverse Speed and Stand-Off Distance on the strain hardened Monel 400. This machining process is found to be more suitable for machining Monel 400 because of notable advantages like lack of thermal damage, lower tool wear, small cutting forces and high productivity as compared to other conventional and non-conventional process. Problem of burr formation and delamination is almost zero with Abrasive Water Jet Machining. The input process parameters are Abrasive Flow Rate, Traverse Speed and Kerf Width. It is observed that the optimal values of the Input parameters are 250gm/min for Abrasive Flow Rate, 140mm/min for Traverse Speed and 3mm for Stand-Off Distance which would provide an optimal Material Removal Rate with minimum Kerf Width and low Surface Roughness.

It is also found that Traverse speed is the factor which gives the major contribution in influencing MRR and Surface Roughness. It is also found that the most influencing factor for Kerf Width is Abrasive Flow Rate.

The regression equation obtained can be used to determine the output parametric values using input values.

Finally the comparative study revealed that the MRR reduces with increase in hardness. It is observed that the Surface roughness and the Kerf Width are reduced with respect to the increase in hardness.

REFERENCES

[1] Elso Kuljanic, Marco Sortino, Giovanni Totis, 2010. “Machinability of difficult machining materials”. For 14th International Research/Expert Conference.
[2] Khan A.A, Haque M.M, 2007. “Performance of different abrasive materials during abrasive water jet machining of glass”. A journal of Material Processing Technology 191(2007) 404-407.
[3]]Vishal Guptaa, Pandeya P.M., Mohinder Pal Garg, Rajesh Khanna, Batrab N.K., 2014. “Minimization of kerf taper angle and kerf width using Taguchi’s method in abrasive water jet machining of marble”. For 3rd International Conference on Materials Processing and Characterisation (ICMPC 2014).
[4] Vasanth S, Muthuramalingam T, Vinothkumar P, Geethapriyan T, Murali G, 2016. “Performance Analysis of Process Parameters on Machining Titanium (Ti-6Al-4V) Alloy Using Abrasive Water Jet Machining Process”. For 7th HPC 2016 – CIRP Conference on High Performance Cutting.
[5] Piotr Loschnera, Krzysztof Jarosza, Piotr Niesłonya, 2016. “Investigation of the effect of cutting speed on surface quality in abrasive water jet cutting of 316L stainless steel”. For International Conference on Manufacturing Engineering and Materials 149 (2016) 276-282.
[6] Divyansh Patel, Puneet Tandom, 2015. “Experimental investigation of thermally enhanced Abrasive Water Jet machining of hard to machine materials”. A CIRP journal of Manufacturing science and Technology.
[7] Fowler. G, Shipway. P.H, Pashby I.R., 2005. “A technical note on grit embedment following abrasive water-jet milling of a titanium alloy”. A Journal of Materials Processing Technology 159 (2005) 356–368.
[8] Puneet Trivedi, Ajit Dhanawade and Shailendra Kumar, 2016. “An experimental investigation on cutting performance of abrasive water jet machining of austenite steel (AISI 316L)”. A Journal of Advances in Materials and Processing Technologies, pp 263-274.
[9] Azmir M.A, Ahsan A.K, 2008. “Investigation on glass/epoxy composite surfaces machined by abrasive water jet machining ”.A Journal of Materials Processing Technology 198 (2008) 122-128.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 05, May - 2017

[10] Boud .F, Carpenter .C, Folkes. J, Shipway P.H, 2010. "Abrasive Water Jet cutting of titanium alloy: the influence of Abrasive morphology and mechanical properties on workpiece grit embedment and cut quality". A journal of Material Processing Technology 210(2010)2197-2205.

[11] Chithirai Pon Selvan M and Dr. N. Mohana Sundara Raju, 2012. "A Machinability Study of Stainless Steel Using Abrasive Waterjet Cutting Technology". For International Conference on Mechanical, Automobile and Robotics Engineering (ICMAR'2012) Penang. Malaysia