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"An investigation and analysis of abrasive water jet cutting process for maraging steel using response surface methodology"

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ABSTRACT: Abrasive water jet cutting is a cutting process which in which abrasive particles are entrained into a jet of water which is accelerated to high velocities by use of pressures normally in excess of 130MPa.The particle-laden water jet impinges onto the surface of the work piece and material is removed by an erosion process. Maraging 300 grade steel is widely used in aerospace and tooling sector because of practical application. It have excellent properties like medium to high carbon material as it doesn't endure issues like high carbon content advancing the erosion or furthermore, making the break. This study investigates the effect of process parameter (like travel speed, abrasive mass flow rate, standoff distance and pressure) on the kerf width, material removal rate and surface roughness. The analysis of variance (ANOVA) and regression models will be developed based on experimental results. In this study, the multi objective optimization has been carried out to find optimal process parameter.

While studying the effect of the process parameters on the material removal rate, it was observed that cutting speed, standoff distance, pressure and abrasive mass flow rate, square effect of abrasive mass flow rate are the influencing parameter.it has been found that standoff distance, square effect of stand of distance are the influencing parameter for kerf width.

The grey relational analysis have suggested the optimum process parameters value of traverse speed of 100 mm/min, 200 gm/min of abrasive mass flow rate, 1 mm of standoff distance and 400 Mpa of pressure. From the confirmation test, it has been found that the suggested model is very excellent in terms of accuracy.

KEYWORDS: Abrasive Water Jet Machine (AWJM), Surface roughness, Material removal rate, Kerf width, Grey Relational Analysis (GRA), Regression.

I. INTRODUCTION

Abrasive Water Jet (AWJ) machining is non traditional or non conventional machining process. Mechanical energy of water and abrasive phases are used to achieve material removal or machining. Profitable technique and can be more competitive than laser cutting if several cutting heads are used. New machining technology in that it makes use of the impact of abrasive material to erode the work piece material. Maraging steel is offering an appealing alternative to the medium to high carbon material as it doesn't endure issues like high carbon content advancing the erosion or furthermore, making the break.

There are many advantages of this such as Cut virtually any material & are very safe extremely fast setups and programming, Very low side forces during the machining, No heat generated on the part, Machine thick plates, Capital cost is low, Clean cutting process without gasses or oils.

Abrasive Water Jet Cutting process applied on many industries like Paint removal, Cleaning, Cutting soft material, Textile & leather industry, Cutting, Drilling, Turning, Pocket milling.

[1] Radovanovic, (2020) has investigated the abrasive water jet cutting process with help of cutting various types of material and thickness of it. For that, it has been used various input parameter like water pressure, water flow rate, orifice diameter, nozzle diameter, abrasive mass flow rate, traverse speed and standoff distance. In order to conduct study, it had used carbon steel S235 as a

material; also applying the multi objective optimization to find optimal process parameter for productivity and operating cost. It had considered three constrain like perpedicularity tolerance, surface roughness limit and traverse speed for separation cut. It has revealed that optimal process parameter at 6.5 mm thick: traverse rate vf=127 mm/min, abrasive flow rate ma=300 g/min and standoff distance h=1 mm. they have concluded that machining time needed to produce a unit of cut surface is t=7.266 s/cm2 (productivity is Q=8.258 cm2/min) and operating cost per meter of cut is C=2.048 EUR/m.

[2] Schwartzentruber, Spelt, & Papini, (2017) have used three dimensional techniques to predicate the surface roughness while cutting of composite material by abrasive water jet cutting process. They have revealed that individual particle of abrasive material would be generated crater which one was follow by the multi particle impact profile in case of two dimensional model for said study. In case of three dimensional model, it can be concluded that the conical crater has been developed until steady surface roughness found. At the end of study. It has been found that average error of 10 % and 16% were found for the 2D & 3D models respectively.

[3] Ravi Kumar, Sreebalaji, & Pridhar (2018) have conducted researched based on the aluminium/ tungsten carbide composites by abrasive water jet cutting process. For that, they have fabricated composite material by using various sizes (like 2, 4, 6, 8 and 10 wt% tungsten carbide) of tungsten carbide. They have used response surface methodology to investigate the said process. They have varied speed of cutting, stand-off distance and percentage of carbide in material to optimize the material removal rate and surface roughness. They have found that the surface roughness is being varied by the carbide content in material. They have seen the breaks, bulge of the tungsten carbide and voids in the material while microstructure examination. Multi Response Optimization dependent on attractive quality is utilized to assess the arrangement of information measure boundaries to increase material removal rate and limiting surface roughness. They have concluded that optimal process parameter are following: standoff distance 4.22mm, cross over speed-223.28 mm/min, and rate tungsten carbide- 2.10%.

[4] Tudor & Andrea, (2013) have carryout the study for optimisation of abrasive jet cutting by means of taguchi methods. They have been influenced the process parameter like jet pressure, feed speed, stand-off distance, abrasive graining, mass flow, etc. The roughness of the machined surfaces and the thickness of the cut part are output quantities of the system, their values depending on the input parameters and the influence of various disturbing factors (noises). They obtained surface roughness consequently to abrasive jet cutting. By assigning these optimum set points to the input quantities the machining system becomes robust, and consequently the roughness of the machined surfaces will not deviate from the desired and predicted value.

[5] Narayanan, Balz, Weiss, & Heiniger, (2013) have developed the model of abrasive particle energy in water jet machining. They took process parameter with wide variations in cutting-head geometry, operating pressure, and abrasive mass flow rates. The cross-sectional averaged abrasive particle velocity at the exit of the focussing tube has been predicted with good accuracy over the whole range of experiments.

[6] Begic-Hajdarevic, Cekic, Mehmedovic, & Djelmic, (2015) have investigated on surface roughness through effects of material thickness, traverse speed and abrasive mass flow rate during abrasive water jet cutting of aluminium. They show that traverse speed has great effect on the surface roughness at the bottom of the cut. They discussed the correlation between the surface roughness and other abrasive water jet cutting variables. The surface being cut by the abrasive water jet was characterized by two types of surface texture. The first texture was located at the beginning of the cut and was characterized by the smooth surface. The second texture was located at the bottom of the cut and was characterized by the rough surface. They suggested optimal solution is the choice of medium traverse speed with which can be achieved higher productivity with acceptable surface roughness.

Problem definition

Facing problem like higher surface roughness of machined surface, lower material removal rate, taper of cutting as well as the kerfwidth in the plate, Kerf taper, the wear of nozzle, limited machining capability.

Confused about following problem.

- How thick is the metal want to cut?
- Traditional way of cutting takes a lot of time.
- The most important factors that influence the cutting process?
- What type of material is to cutting?
- What are the best conditions to achieve optimum performances?

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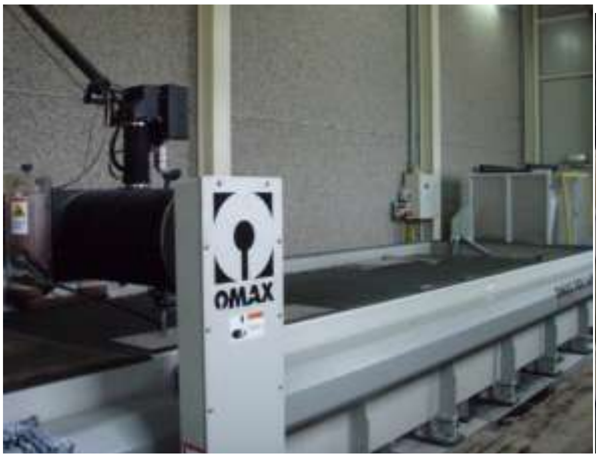
II. EXPERIMENTAL SETUP AND DETAILS



The equipment used for machining the samples will Abrasive Water Jet 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 sheared between the Jet machining centre controller and the pump.

Maraging steel is offering an appealing alternative to the medium to high carbon material as it doesn't endure issues like high carbon content advancing the erosion or furthermore, making the break. These may be answerable for the startling disappointment of the part or the durability. The low carbon substance of maraging steel diminishes the danger of unpredicted failure. Generally, the maraging steel are widely popular in die and mould making industries as aforesaid reasons. Moreover, the H13, P20 steel is used to make the die and mould, but it have high carbon percentage which leads aforesaid problem. The application of the maraging steel does not limit upto the tooling industries, but it also widely used in aerospace and automotive sector as has excellent corrosion resistance and high remarkable mechanical properties[7]-[9]. Experimental specimens having dimension 850mm X 150mm x 14mm have been prepared for the experimental work. The material for test specimen is maraging steel 300 grades.

Table 2.1 Chemical composition of maraging steel 300 grade.

Element	Grade 300
Iron	Balance
Nickel	**18.0-19.0**
Cobalt	8.5-9.5
Molybdenum	4.6-5.2
Titanium	0.5-0.8
Aluminum	0.05-0.15

Process parameters:

The process parameters include parameters relating to the forming of the AWJ. These parameters can be sorted into four following sub-groups :

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1. Hydraulic parameters including water pressure and orifice diameter.
2. high pressure water
3. orifice abrasive supply mixing chamber focusing tube

-Mixing parameters including focusing tube (or nozzle) diameter and focusing tube length.

Abrasive parameters including
1. abrasive material,
2. abrasive particle size,
3. abrasive shape, and
4. abrasive mass flow rate.

Cutting parameters including
1. standoff distance,
2. impact angle,
3. traverse rate and
4. number of passes.

III. METHODOLOGY

3.1 Design of experiment

Design of experiment is powerful way to deal with limit the quantity of analyses yet separate all the information about the reliance of result on the procedure boundaries. It is basic to follow a methodology of experimentation where input boundaries of procedure might be fluctuated all the while to contemplate their impact on the procedure yield. The connection among yield and at least one info process boundaries might be direct or non straight in nature. The choice of structure of trials relies upon the straight or the non-direct nature of the procedure. The information about nature of variety is important to sort the issue either as straight or non-direct [10].

3.2 Analysis of variance (ANOVA)

The aim of this research, to analyzed the output response parameters like MRR (mm^3/min), Surface roughness (µm), Kerf width (mm) by Considering Traverse speed (mm/min), Abrasive mass flow rate (gm/min), Stand-off distance(mm), Pressure (MPa) as input parameters for VCR engine. The corresponding response parameters were noted, when experiments are carried out as per the run order of the minitab-17 input parameters given by Box behnkhen method. The model was analyzed by using Analysis of variance (ANOVA). RSM was used for optimized output parameters with highest desirability.

3.3 RSM Methodology

There are four types of design experiments such as Factorial, Response surface, mixture and Taguchi in Minitab. Minitab provides analytical and graphical tools to help understand the results after the following steps to crate, analyze, and graph of experimental design.

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize response. In practice the requirement of RSM for to chose the sample point such that the sufficient accurate model can be generated with the minimum number of experiments. Response Surface Method is used to examine the relationship between a response and a set of quantitative experimental variables or factors.

3.4 Determination of independent variables and their levels

Select the parameters (variable) that have major effects on output. The levels of the parameters are determined. All variable will be tested over the same range. Range of the variable are forced between the ranges of coded variable -1 to 1. Equation of coding is given below:

$$X = (x-[x_{max}+x_{min}]/2)/([x_{max}-x_{min}]/2) \quad \ldots\ldots(1.1)$$

Where, X = coded variable
x = natural variable
xmax ,xmin = maximum and minimum values of the natural variable.

3.5 Box-Behnken Method

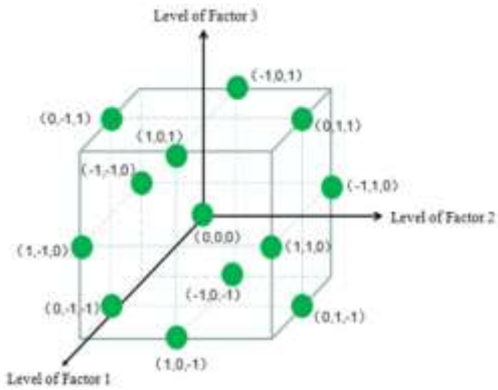

Figure 3.1 Box–Behnken designs for three factors

Appeared differently in relation to the CCD, this structure has preferences. The three-factor BBD requires just 12 test runs with notwithstanding the repeats at the inside point, while its CCD has 14 non-focus focuses. Generally speaking, the amount of test focuses is given by 2k(k−1) + nc (where, k= no. of factor and nc = runs at focus). Similarly, each factor is learned at only three levels, with some critical highlights in some exploratory circumstance. While, using α = 1 out of a CCD also achieves three levels for each factor. In

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most certified applications, these differentiations are apparently not unequivocal in making sense of which configuration to use, in any occasion for this number of variables. In various sensible assessments that require RSM, specialists are inclined to require three fairly scattered levels. Thusly, the BBD is a beneficial decision and point of fact an imperative differentiating choice to the CCD (Yang, 2008). Note that the Box–Behnken plan (BBD) is very equivalent in various structure focuses to the CCD for k = 3 and k = 4. (There is no BBD for k = 2). For k = 3, the CCD contains 14+ nc runs while the BBD contains 12+ nc runs. For k = 4 the CCD and BBD both contain 24+ nc structure points. In BBD, just three degrees of procedure boundary have been required to run the investigation, likewise there is no focuses lie on the vertices of the trial region. This is the fundamental trait of the BBD techniques [11], [12], [12]–[14].

Box-Behnken structures never incorporate runs where all elements are at their extraordinary setting, for example, the entirety of the low settings, in contrast to focal composite plans. Besides, In Box-Behnken structure there are less plan focuses than focal composite structures which brings about more affordable to run with a similar number of variables. Response Surface strategies are utilized to look at the connection between at least one reaction factors and a lot of quantitative exploratory factors or factors. These strategies are frequently utilized after distinguished the significant controllable variables and to discover the factor choice that upgrades the reaction [15], [16].

Table 3.1 - Range of process parameter

Parameters	Unit	Level 1	Level 2	Level 3
Traverse speed	Mm/min	100	150	200
Abrasive mass flow rate	g/min	200	250	300
Stand off distance	Mm	0.5	0.75	1
Pressure	Mpa	300	400	500

Table 3.2 Box-Behnken design for experiment work in actual foam

Sr. no.	Travers e speed	Abrasiv e mass flow rate	Stand off distanc e	Pressur e
1.	100	200	0.75	400
2.	200	200	0.75	400
3.	100	300	0.75	400
4.	200	300	0.75	400
5.	150	250	0.50	300
6.	150	250	1.00	300
7.	150	250	0.50	500
8.	150	250	1.00	500
9.	100	250	0.75	300
10.	200	250	0.75	300
11.	100	250	0.75	500
12.	200	250	0.75	500
13.	150	200	0.50	400
14.	150	300	0.50	400
15.	150	200	1.00	400
16.	150	300	1.00	400
17.	100	250	0.50	400
18.	200	250	0.50	400
19.	100	250	1.00	400
20.	200	250	1.00	400
21.	150	200	0.75	300
22.	150	300	0.75	300
23.	150	200	0.75	500
24.	150	300	0.75	500

25.	150	250	0.75	400
26.	150	250	0.75	400
27.	150	250	0.75	400

3.6 Performance characteristics

3.6.1 Surface Roughness

Roughness is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small the surface is smooth. Roughness is typically considered to be the high frequency, short wavelength component of a measured surface. Surface roughness normally measured. Roughness plays an important role in determining how a real object will interact with its environment. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces (see tribology). Roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks or corrosion. In this thesis, the average surface roughness is measured and calculated. The average surface roughness is the integral of the absolute value of the roughness profile height over the evaluation length and is denoted by the following equation [17], [18].

$$\mathrm{Ra} = \frac{1}{L\int_0^L Y(x)dx}$$

Where L is the length taken for observation, and Y is the ordinate of the profile curve.

Fig 3.2 Surface roughness tester

Table 3.3 Specification of surface roughness tester

Manufacturer	Mitutoyo SJ210
Travelling length	01mm to 50mm
Force	4Mn
Stylus	Diamond 2μm tip radius
LCD dimension	36.7 X 48.9 mm
Mass	500g

3.6.2 Kerf Width

Kerf width is one of the important performance measures in WEDM. Kerf width is the measure of the amount of the material that is wasted during machining. It determines the dimensional accuracy of the finishing part. The internal corner radius to be produced in WEDM operations are also limited by the Kerf width [19], [20]. The setup for the kerf width is shown in fig. 3.3. the technical specification of the profile projector as per table 3.4.

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Fig 3.3 profile projector

Table 3.4 specification of the profile projector

Item	Specification
Optical Head	45º inclined Monocular Head; Rotatable
Stage	60mm black/white stage plate and paired clips
Focuser	Rack and Pinion
Objective	4x; Working Distance 58mm
Eyepiece	10x; 18mm

3.6.3 Material removal rate

The material removal rate can be defined as the volume of material removed divided by the machining time. Material Removal Rate (MRR) is defined by following formula [21], [22].

$$MRR = (W_i - W_f) / (\rho_w T)$$

Where,
W_i = initial weight of work piece (g)
W_f = final weight of work piece material (g)
T = cutting time(s)
ρ_w = Work piece density (g/ mm3)

Fig.3.4 Digital weighting scale

Table 3.5 Specification of the Digital weighting scale

Max. Capacity	210g
Readability	0.0001g
Repeatability	0.0001g
Linearity	0.0003g

Adjustment weight internal	No
Adjustment weight external	200g

IV. RESULT

The experimental result, effect of process parameter like Traverse speed (mm/min), Abrasive mass flow rate (gm/min), Stand-off distance (mm) and Pressure (MPa) on the responses like material removal rate, surface roughness and kerf width. Analysis of various table for the aforesaid response.

Table 4.1 Experimental Readings

Column	Define
A1	Sr. no
A2	Traverse speed (mm/min)
A3	Abrasive mass flow rate (gm/min)
A4	Stand-off distance(mm)
A5	Pressure (MPa)
A6	MRR (mm^3/min)
A7	Surface roughness (µm)
A8	Kerf width (mm)

A1	A2	A3	A4	A5	A6	A7	A8
1	100	200	0.75	400	5.38	6.34	1.28
2	200	200	0.75	400	5.52	2.34	1.30
3	100	300	0.75	400	5.55	2.40	1.31
4	200	300	0.75	400	5.60	3.50	1.26
5	150	250	0.50	300	5.11	2.57	1.27
6	150	250	1.00	300	5.37	3.91	1.56
7	150	250	0.50	500	5.45	3.46	1.25
8	150	250	1.00	500	5.49	2.94	1.56
9	100	250	0.75	300	5.22	4.56	1.28
10	200	250	0.75	300	5.55	4.06	1.27
11	100	250	0.75	500	5.50	3.03	1.27
12	200	250	0.75	500	5.61	2.70	1.28
13	150	200	0.50	400	5.20	4.51	1.23
14	150	300	0.50	400	5.37	2.30	1.24
15	150	200	1.00	400	5.58	3.87	1.65
16	150	300	1.00	400	5.70	2.12	1.57
17	100	250	0.50	400	5.11	4.08	1.25
18	200	250	0.50	400	5.45	3.84	1.27
19	100	250	1.00	400	5.35	4.51	1.56
20	200	250	1.00	400	5.59	4.29	1.53
21	150	200	0.75	300	5.54	3.97	1.27
22	150	300	0.75	300	5.44	3.57	1.20
23	150	200	0.75	500	5.24	3.40	1.22
24	150	300	0.75	500	5.90	2.35	1.25
25	150	250	0.75	400	5.43	4.43	1.24
26	150	250	0.75	400	5.44	4.44	1.24
27	150	250	0.75	400	5.44	4.42	1.25

4.2 Main effect of input parameter on the response

In this section, it has been discussed the effect of various input parameter like Traverse speed (mm/min), Abrasive mass flow rate (gm/min), Pressure (MPa) and Stand-off distance (mm)on the targeted response like material removal rate, surface roughness and kerf width.

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4.2.1 Main Effects Plot of material removal rate

The main effects plot for material removal rate versus Traverse speed (mm/min), Abrasive mass flow rate (gm/min), Pressure (MPa) and Stand-off distance (mm)is shown in fig.4.2, which is generate from the value of material removal rate as per table 4.1 in minitab-17 statistical software. It is useful to find out optimum parameter value for response variable. Fig. 4.2 shows that high material removal rate will meet at transverse speed 200 mm/min, 300 gm/min of abrasive flow rate, 1 mm of stand of distance and 500 Mpa of pressure. The graph generates by use of minitab-17 statistical software for material removal rate is shown in fig. 4.2

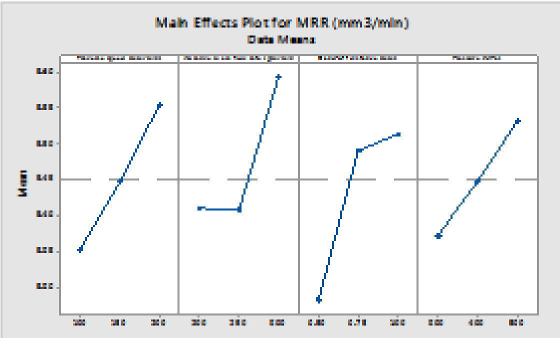

Fig. 4.2 Effect of control factor on material removal rate

From the fig. 4.2, it has been concluded that the optimum combination of each process parameter for high material removal rate is meeting at high cutting speed[A3], high abrasive mass flow rate [B3], high standoff distance[C3] and high pressure [D3].

This aforesaid combination is representing the single objective response optimization where material removal rate is getting higher without considering other response. The reason behind this optimum process parameter has been discussed here. It very well may be seen that the Width of the grating plane progressively grows because of spreading as the separation from spout tip increments and therefore speed (or kinetic energy) of the rough particles diminishes. Since kinetic energy bestowed by the abrasive is utilized to bit by bit dissolve material from work surface, bigger standoff distance brings about lower infiltration just as lower material material rate. Then again, in the event that stand off distance is too little, adequate section won't be accessible for the pre-owned rough abrasive to come out from the machining zone after impact. It can considerably reduced speed of new abrasive as a result of impact that can prompt decreased adequacy of the jet regarding material disintegration. Hence, at first with expansion in standoff distance, both the MRR and entrance increment slowly; notwithstanding, after certain breaking point, both diminishing with additional increment in standoff distance. Along these lines an ideal worth of deadlock distance is needed for acquiring good execution in rough stream machining.

4.2.2 Main Effects Plot of Kerf width

The main effects plot for kerf width versus Traverse speed (mm/min), Abrasive mass flow rate (gm/min), Pressure (MPa) and Stand-off distance (mm)is shown in fig.4.3.

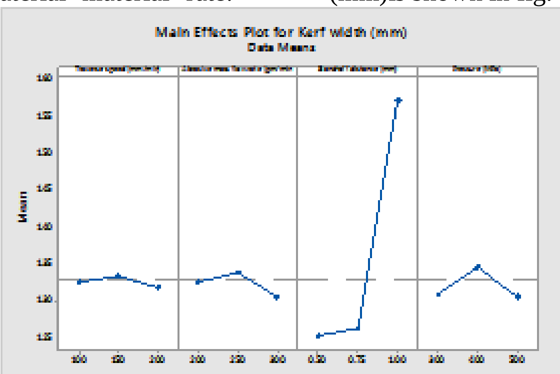

Fig. 4.3 Effect of control factor on Kerf width

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From the fig.4.3, it has been conclude that the optimum combination of each process parameter for low Kerf width is meeting at high cutting speed [A3], high abrasive mass flow rate [B3], low stand off distance[C1] and high pressure [D3].

This aforesaid combination is representing the single objective response optimization where Kerf width is getting lower without considering other response. The reason behind this optimum process parameter has been discussed here. It has been seen that the rough particles have an adequate degree of active energy to destruct the material. This little harmed district is portrayed by a little adjusted corner at the top edge because of the plastic miss happening of material brought about by the underlying AWJ assault. As the grating particles infiltrate into the material, a portion of the energy is utilized in disintegrating the material in loses dynamic energy. A fly with lower energy will in general avoid the typical way to the plane of cutting, which will bring about striations to be shaped on the cutting surface. As the rough fly stream crosses the part, the stream is diverted, henceforth bringing about the formation of a one of a kind cutting math. The level of diversion increments with speeding up.

4.2.3 Main Effects Plot of surface roughness

The main effects plot for surface roughness versus Traverse speed (mm/min), Abrasive mass flow rate (gm/min), Pressure (MPa) and Stand-off distance (mm)is shown in fig.4.4, which is generate from the value of kerf width as per table 4.1 in minitab-17 statistical software. It is useful to find out optimum parameter value for response variable. Fig.4.3 shows that the lower surface roughness will meet at transverse speed 200 mm/min, 300 gm/min of abrasive flow rate, 0.5 mm of stand of distance and 500 Mpa of pressure.The graph generate by use of minitab-17 statistical software for material removal rate is shown in fig.4.2

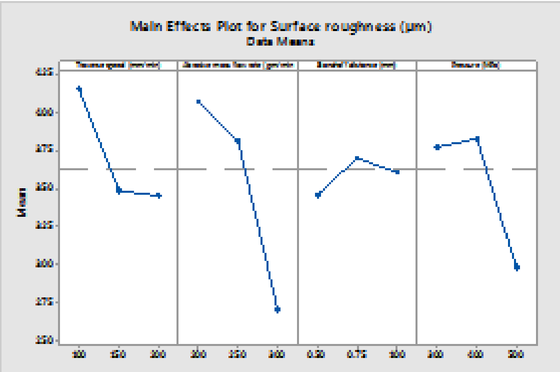

Fig. 4.4 Effect of control factor on surface roughness

From the fig.4.3, it has been conclude that the optimum combination of each process parameter for low surface roughness is meeting at high cutting speed [A3], high abrasive mass flow rate [B3], low stand off distance [C1] and high pressure [D3].

This aforesaid combination is representing the single objective response optimization where surface roughness is getting lower without considering other response. From the test results, it very well may be seen that an increment in the cutting speed causes a consistent expansion in the surface unpleasantness. This might be expected as expanding cutting speed permits less cover machining activity and less grating particles to encroach the surface, reducing the surface finish.

4.3 Analysis of Variance

In this section, the analysis of variance for the responses like material removal rate and surface roughness has been discussed. The analysis of variance is representing the effect of the input parameter on the responses in terms of the p- test and F test.

Analysis of variance (ANOVA) is a statistical model which can be used for find out effect of independent parameter on single dependent parameter and also it can be use full to find out the significant machining parameters and the percentage contribution of each parameter.

4.3.1 Analysis of Variance for the material removal rate

According to the analysis done by the MINITAB 17 software, if the values of probability are less than 0.05, it indicated that the factors are significant to the response parameters. Comparing the p-value to a commonly used α- level = 0.05, it is found that if the p- value is less than or equal to α, it can be concluded that the effect is significant.

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Table no. - 4.2 Analysis of variance for the material removal rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	0.73271	0.052336	8.59	0
Linear	4	0.46065	0.115162	18.91	0
A	1	0.122008	0.122008	20.04	0.001
B	1	0.100833	0.100833	16.56	0.002
C	1	0.161008	0.161008	26.44	0
D	1	0.0768	0.0768	12.61	0.004
Square	4	0.09831	0.024578	4.04	0.027
A*A	1	0.00049	0.00049	0.08	0.782
B*B	1	0.037037	0.037037	6.08	0.03
C*C	1	0.028356	0.028356	4.66	0.052
D*D	1	0.00037	0.00037	0.06	0.809
2-Way InteractioN	6	0.17375	0.028958	4.76	0.011
A*B	1	0.002025	0.002025	0.33	0.575
A*C	1	0.0025	0.0025	0.41	0.534
A*D	1	0.0121	0.0121	1.99	0.184
B*C	1	0.000625	0.000625	0.1	0.754
B*D	1	0.1444	0.1444	23.71	0
C*D	1	0.0121	0.0121	1.99	0.184
Error	12	0.073075	0.00609		
Lack-of-Fit	10	0.073008	0.07301	19.02	0.5
Pure Error	2	0.000067	0.000033		
Total	26	0.805785			

Model Summary

S	R-sq	R-sq(adj)
0.0780358	90.93%	80.35%

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From ANOVA result it is observed that the cutting speed, standoff distance, pressure and abrasive mass flow rate, square effect of abrasive mass flow rate are the influencing parameter for material removal rate as they are all less than 0.05 p. The confidence level (CL) used for investigation is taken 95% for this investigation. The parameter R-Sq described the amount of variation observed in material removal rate is explained by the input factor. R-Sq= 90.93% which indicate that the model is able to predicate the response with high accuracy.

4.3.2 Analysis of variance for Kerf width

From ANOVA result it is observed that the pulse on, wire feed rate, current, effect of square effect of pulse of, wire feed rate and effect of two way interaction of pulse off versus wire feed, and effect of two interaction of pulse off versus current are influencing parameter for Kerf width as they are all less than 0.05 p.

Table 4.3 Analysis of variance for the Kerf width

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	0.469057	0.033504	39.61	0
Linear	4	0.308567	0.077142	91.2	0
A	1	0.000133	0.000133	0.16	0.698
B	1	0.0012	0.0012	1.42	0.257
C	1	0.3072	0.3072	363.19	0
D	1	0.000033	0.000033	0.04	0.846
Square	4	0.153916	0.038479	45.49	0
A*A	1	0.002601	0.002601	3.07	0.105
B*B	1	0.000779	0.000779	0.92	0.356
C*C	1	0.131601	0.131601	155.59	0
D*D	1	0.000001	0.000001	0	0.974
2-Way InteractioN	6	0.006575	0.001096	1.3	0.33
A*B	1	0.001225	0.001225	1.45	0.252
A*C	1	0.000625	0.000625	0.74	0.407
A*D	1	0.0001	0.0001	0.12	0.737
B*C	1	0.002025	0.002025	2.39	0.148
B*D	1	0.0025	0.0025	2.96	0.111
C*D	1	0.0001	0.0001	0.12	0.737
Error	12	0.01015	0.000846		

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Lack-of-Fit	10	0.010083	0.001008	3.25	0.32
Pure Error	2	0.000067	0.000033		
Total	26	0.479207			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0290832	97.88%	95.41%	87.85%

From ANOVA result it is observed that the stand off distance, square effect of stand of distance are the influencing parameter for kerf width as they are all less than 0.05 p. The confidence level (CL) used for investigation is taken 95% for this investigation. The parameter R-Sq described the amount of variation observed in kerf width is explained by the input factor. R-Sq= 97.88% which indicate that the model is able to predicate the response with high accuracy.

4.3.3 Analysis of variance for surface roughness

From ANOVA result, table 3.4, it is observed that the abrasive mass flow rate, pressure square effect of abrasive mass flow rate, two way interaction effect of cutting speed and abrasive mass flow rate are influencing parameter for surface roughness as they are all less than 0.05 p.

Table 4.4 Analysis of variance for the surface roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	20.8508	1.48934	4.78	0.005
Linear	4	9.0054	2.25134	7.23	0.003
A	1	1.463	1.46301	4.7	0.051
B	1	5.5897	5.58968	17.95	0.001
C	1	0.0645	0.06453	0.21	0.657
D	1	1.8881	1.88813	6.06	0.03
Square	4	4.3122	1.07806	3.46	0.042
A*A	1	0.0064	0.00638	0.02	0.889
B*B	1	2.3027	2.30271	7.39	0.019
C*C	1	1.0364	1.03645	3.33	0.093
D*D	1	2.436	2.436	7.82	0.016
2-Way Interaction	6	7.5332	1.25554	4.03	0.019
A*B	1	6.5025	6.5025	20.88	0.001
A*C	1	0.0001	0.0001	0	0.986
A*D	1	0.0072	0.00722	0.02	0.881

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B*C	1	0.0529	0.0529	0.17	0.687
B*D	1	0.1056	0.10562	0.34	0.571
C*D	1	0.8649	0.8649	2.78	0.121
Error	12	3.7368	0.3114		
Lack-of-Fit	10	3.7366	0.37366	3736.6	0
Pure Error	2	0.0002	0.0001		
Total	26	24.5876			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.558033	84.80%	67.07%	12.46%

The confidence level (CL) used for investigation is taken 95% for this investigation. The parameter R-Sq described the amount of variation observed in surface roughness is explained by the input factor. R-Sq= 84.80 % which indicate that the model is able to predicate the response with high accuracy.

4.4 REGRESSION MODEL

The regression model for predicting the response parameters in turning can be derived using methods like Regression analysis.

Regression analysis is often used to:

- Determine how the response variable changes as particular predictor variable changes.
- Predict the value of the response variable for any value of the predictor variable, or combination of values of the predictor variables.

4.4.1 Regression Equation for Material removal rate

The regression equation for the material removal rate is following:

Material removal rate (mm3/min) =

7.39 + 0.00902 A - 0.02793 B + 3.64 C - 0.00607 D + 0.000004 A*A + 0.000033 B*B - 1.167 C*C + 0.000001 D*D - 0.000009 A*B - 0.00200 A*C- 0.000011 A*D - 0.00100 B*C + 0.000038 B*D - 0.00220 C*D ....(4.1)

4.4.2 Regression Equation for Kerf width

The regression equation for the kerf width is following:

Kerf width (mm) =

2.645 - 0.00062 A - 0.00222 B - 2.610 C - 0.00153 D + 0.000009 A*A + 0.000005 B*B + 2.513 C*C - 0.000000 D*D - 0.000007 A*B - 0.00100 A*C+ 0.000001 A*D - 0.00180 B*C + 0.000005 B*D + 0.000200 C*D.......................................(4.2)

4.4.3 Regression Equation for surface roughness

The regression equation for the surface roughness is following:

Surface roughness =

-8.7 - 0.1340 A + 0.0474 B + 15.95 C + 0.0709 D - 0.000014 A*A- 0.000263 B*B - 7.05 C*C - 0.000068 D*D + 0.000510 A*B + 0.0004 A*C+ 0.000008 A*D + 0.0092 B*C - 0.000033 B*D - 0.0186 C*D...(4.3)

V. MULTI OBJECTIVE OPTIMIZATION

5.1 Grey Relational Analysis

The grey relational analysis, a grey relational grade can be obtained to evaluate the multiple performance characteristic. As a result, optimization of the complicated multiple performance characteristic can be converted into the optimization of a single grey relation grade. For multiple performance characteristic optimizations using GRA, following steps are followed:

1. Conduct the experiments of different settings of parameters based on available design of experiment.
2. Normalization of experimental result for all performance characteristics.

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3. Performance of grey relational generating and calculation of grey relational coefficient (GRC).
4. Calculation of grey relation grade using weighing factor for performance characteristics.
5. Analysis of experimental results using GRG and statistical analysis of variance (ANOVA).
6. Selection of optimal levels of process parameters.
7. Conducting confirmation experiment to verify optimal process parameter settings.

Table 5.1 Experimental value and Normalized value of response

Sr. no.	MRR (mm^3/min)	Surface roughness (µm)	Kerf width (mm)	MRR (mm^3/min)	Surface roughness (µm)	Kerf width (mm)
				Normalization		
1	5.38	6.34	1.28	0.341772	0	0.822222
2	5.52	2.34	1.30	0.518987	0.947867	0.777778
3	5.55	2.40	1.31	0.556962	0.933649	0.755556
4	5.60	3.50	1.26	0.620253	0.672986	0.866667
5	5.11	2.57	1.27	0	0.893365	0.844444
6	5.37	3.91	1.56	0.329114	0.575829	0.2
7	5.45	3.46	1.25	0.43038	0.682464	0.888889
8	5.49	2.94	1.56	0.481013	0.805687	0.2
9	5.22	4.56	1.28	0.139241	0.421801	0.822222
10	5.55	4.06	1.27	0.556962	0.540284	0.844444
11	5.50	3.03	1.27	0.493671	0.78436	0.844444
12	5.61	2.70	1.28	0.632911	0.862559	0.822222
13	5.20	4.51	1.23	0.113924	0.433649	0.933333
14	5.37	2.30	1.24	0.32911	0.957346	0.911111

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				4		
15	5.58	3.87	1.65	0.594937	0.585308	0
16	5.70	2.12	1.57	0.746835	1	0.177778
17	5.11	4.08	1.25	0	0.535545	0.888889
18	5.45	3.84	1.27	0.43038	0.592417	0.844444
19	5.35	4.51	1.56	0.303797	0.433649	0.2
20	5.59	4.29	1.53	0.607595	0.485782	0.266667
21	5.54	3.97	1.27	0.544304	0.561611	0.844444
22	5.44	3.57	1.20	0.41772	0.656398	1
23	5.24	3.40	1.22	0.164557	0.696682	0.955556
24	5.90	2.35	1.25	1	0.945498	0.888889
25	5.43	4.43	1.24	0.405063	0.452607	0.911111
26	5.44	4.44	1.24	0.417722	0.450237	0.911111
27	5.44	4.42	1.25	0.417722	0.454976	0.888889

Table 5.2 Grey relational grade (GRG)

Sr. no.	MRR (mm^3/min)	Surface roughness (µm)	Kerf width (mm)	**GRG**
	Grey relational coefficient			
1	0.593985	1	0.378151	0.657379
2	0.490683	0.345336	0.391304	0.409108
3	0.473054	0.34876	0.39823	0.406681
4	0.446328	0.426263	0.365854	0.412815
5	1	0.358844	0.371901	0.576915

6	0.603053	0.464758	0.714286	0.594032
7	0.537415	0.422846	0.36	0.440087
8	0.509677	0.38294	0.714286	0.535634
9	0.782178	0.542416	0.378151	0.567582
10	0.473054	0.480638	0.371901	0.441864
11	0.503185	0.389299	0.371901	0.421461
12	0.441341	0.366957	0.378151	0.395483
13	0.814433	0.535533	0.348837	0.566268
14	0.603053	0.343089	0.354331	0.433491
15	0.456647	0.460699	1	0.639115
16	0.401015	0.333333	0.737705	0.4906
17	1	0.482838	0.36	0.614279
18	0.537415	0.457701	0.371901	0.455672
19	0.622047	0.535533	0.714286	0.623955
20	0.451429	0.507212	0.652174	0.536938
21	0.478788	0.470982	0.371901	0.440557
22	0.544828	0.432377	0.333333	0.436846
23	0.752381	0.417822	0.343511	0.504571
24	0.333333	0.345902	0.36	0.346412
25	0.552448	0.524876	0.354331	0.477218
26	0.544828	0.526185	0.354331	0.475114
27	0.544828	0.523573	0.36	0.476134

5.2 Main Effect of Factors on Grey Relational Grade (GRG)

For the combined response maximizatoin, fig.5.1 gives optimum value of each control factor. It interprets that level A1, B1, C3 and D2. The desired result of each response namely maximum material removal rate, minimum kerf width and minimum surface roughness has been attained at the value of traverse speed of 100 mm/min, 200 gm/min of abrasive mass flow rate, 1 mm of stand off distance and 400 Mpa of pressure. The mean of grey relational grade for each level of the other machining parameters can be computed in similar manner.

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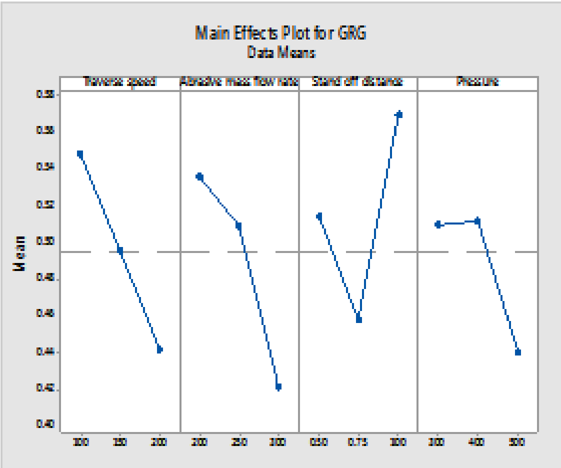

Fig 5.1 – Main effect of factor on Grey Relational Grade

Table 5.3 Main effect of factors on Grey Relational Grade

Symbol	Control factor	Level 1	Level 2	Level 3
A	Traverse speed	**0.5485**	0.4955	0.4419
B	Abrasive mass flow rate	**0.5361**	0.5088	0.4211
C	Standoff distance	0.5144	0.4579	**0.5700**
D	Pressure	0.5096	**0.5116**	0.4406

As per the grey relational theory, it can be said that higher grey relational grade value will give optimum value of material removal rate, surface roughness and Kerf width. Thus it is revealed that response will be optimum at value of traverse speed of 100 mm/min, 200 gm/min of abrasive mass flow rate, 1 mm of stand off distance and 400 Mpa of pressure.

VI. CONCLUSION

In this study, the experimental investigation and analysis are carried out on AISI1045 steel material by using abrasive water jet cutting process. The following conclusions are made.

1. The material removal rate is increased with increase of cutting speed, stand off distance, pressure and abrasive mass flow rate. It has been observed that the high material removal rate will meet at transverse speed 200 mm/min, 300 gm/min of abrasive flow rate, 1 mm of stand of distance and 500 Mpa of pressure.
2. While studying the effect of the process parameters on the material removal rate, it was observed that cutting speed, standoff distance, pressure and abrasive mass flow rate, square effect of abrasive mass flow rate are the influencing parameter.
3. The optimum condition for surface roughness is A3 B3 C1 D3. The said combination is like, lower surface roughness will meet at transverse speed 200 mm/min, 300 gm/min of abrasive flow rate, 0.5 mm of stand of distance and 500 Mpa of pressure.
4. It has concluded that optimum kerf width can be attained at the, transverse speed 200 mm/min, 300 gm/min of abrasive flow rate, 0.5 mm of stand of distance and 500 Mpa of pressure. From the table of analysis of variance, it has been found that stand off distance, square effect of stand of distance are the influencing parameter for kerf width.
5. Thus, aforesaid single objective optimization can be provided / utilized for the single targeted goal. Hence engineer can be targeting the response as per requirement. However, in multi contradictorily goal, multi-objective optimization has been applied.
6. The grey relational analysis have suggested the optimum process parameters value of traverse speed of 100 mm/min, 200 gm/min of abrasive mass flow rate, 1 mm of standoff distance and

400 Mpa of pressure.

7. From the confirmation test, it can be seen that the error between the predicted and actual experiment are less that the -/+10 %. Hence, it can be said that the predication accuracy of suggested model is excellent.
8. Regression analysis have been carried out simultaneously for the individual response, so, engineer can manipulate value of process parameters for this particular work- material.

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