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Optimization of Abrasive Water Jet Machining Process Parameters for Duplex Stainless Steel-2205 by Using Response Surface Methodology

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ABSTRACT

Abrasive Water Jet Machining is a versatile and fastest growing machining process and primarily used in machining of hard and difficult materials.It is also used in machining of soft, thick, light, thin and fragile materials. It compliments other technologies such as Milling, Laser, EDM etc…. It doesn't possess any mechanical stress to operator and environmental hazards. AWJM cut the material accurately unlike any other machining process.AWJM is mainly adopted in aerospace industry for cutting high strength materials and other composites. It finds most of its applications in machining of gas turbines, rocket motors, space craft, nuclear power and pumps etc., A very thin stream of about 0.004 to 0.010 dia. can be cut and material loss is also less due toaccurate cutting. Standoff distance between mixing tube and work part is typically 2 to 4mm important to keep to a minimum to get superior surface finish.The objective of this research is to analysis the effect of input process parameters and to optimize process parameters for achieving optimizing Processes responses such as Metal Removal Rate,Surface roughness and Dimensional deviation simultaneously while machining on the Austenite-Ferrite based alloy DUPLEX STAINLESS STEEL 2205 using AWJM process. It is a precipitation hardened material and has good creep-rupture strength. It shows good mechanical properties even at high temperatures. Applications are Intricate shapes can be easily obtained for Aerospace products ,Metal Matrix Composite & Ceramic Matrix Composite.

Keywords : AWJM, Material Removal Rate, Surface Roughness, Dimensional Deviation, Optimization

Nomenclature :

AWJM : Abrasive water jet machine

MRR : material removal rate

DOE : Design of experiments

I. INTRODUCTION

Water jets were introduced in the United States during the 1970's, and were utilized merely for cleaning purposes. As the technology developed to include abrasive water jets, new applications were discovered. However, until recently this tool had not been used to a great extent in the construction industry.The water jet has shown that it can do things that other technologies simply cannot. From cutting thin details in stone, glass and metals; to rapid hole drilling of titanium; to cutting of food, to the killing of pathogens in beverages and dips, the water jet has proven itself unique.

Water jet machining is a mechanical energy based non-traditional machining process used to cut and machine soft and non-metallic materials. It involves the use of high velocity water jet to smoothly cut a soft work piece. In water jet machining, high velocity water jet is allowed to strike a given work piece. During this process its kinetic energy is converted to pressure energy. This induces a stress on the work piece. When this induced stress is high enough, unwanted particles of the work piece are automatically removed.

The apparatus of water jet machining consists of the following components:

Reservoir: It is used for storing water that is to be used in the machining operation.

Pump: It pumps the water from the reservoir. High pressure intensifier pumps are used to pressurize the water as high as 55,000 psi. For the abrasive water jet, the operating pressure ranges from 31,000 to 37,000 psi. At this high pressure the flow rate of the water is reduced greatly.

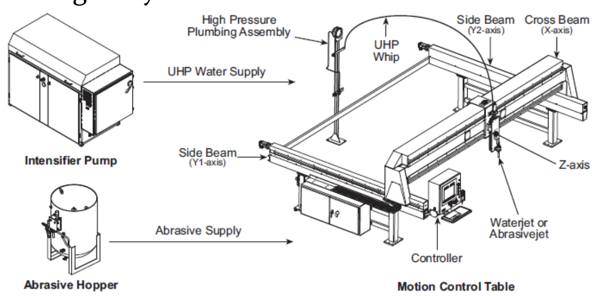


Figure 1. Setup of Abrasive water jet machining process

Intensifier: It is connected to the pump. It pressurizes the water acquired from the pump to a desired level.

Accumulator: It is used for temporarily storing the pressurized water. It is connected to the flow regulator through a control valve.

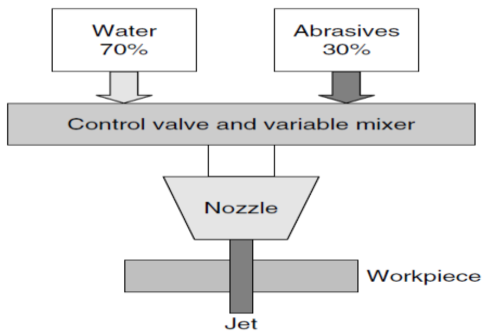
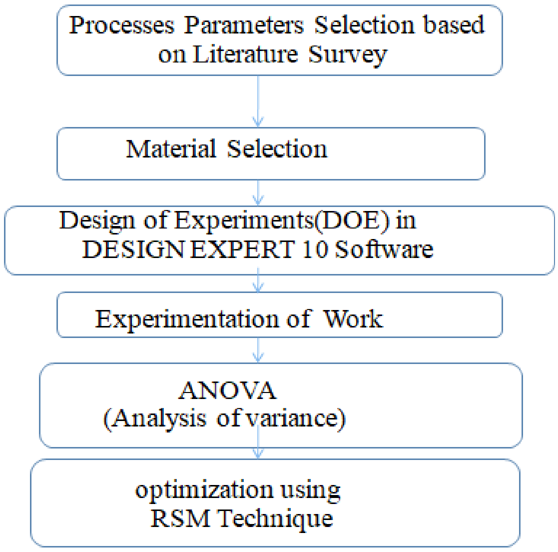


Figure 2. Abrasive and water mixing

Control Valve: It controls the direction and pressure of pressurized water that is to be supplied to the nozzle.

Flow regulator: It is used to regulate the flow of water.

Methodology (or) Step by Step procedure followed in present work



Optimizing Techniques

Taguchi Technique:

Dr. Genechi Taguchi is a Japanese researcher who spent quite a bit of his expert life examining approaches to enhance the nature of fabricated items. After World War II, the Japanese phone framework was gravely harmed and useless. Taguchi was designated as leader of Japan's recently framed Electrical Communications Laboratories (ECL) of Nippon Telephone and Telegraph Company. Quite a bit of his exploration at ECL included building up a thorough quality change philosophy that included utilization of the DOE strategy.

ResponseSurface Methodology:

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques that are useful for modeling and analysis of problems in which the response is influenced by several variables and the main aim is to find the correlation between the response and the variables i.e., it can be used for optimizing the response. In the present study water pressure, abrasive flow rate, orifice diameter, focusing nozzle diameter and standoff distance are chosen as the process parameters and varied at three levels and the commonly used constant parameters of AWJM. In Response surface design, a Box-Behnken design table with 24 experiments was selected.

Genetic Algorithm:

Genetic algorithms have been used in science and engineering as adaptive algorithms for solving practical problems and as computational models of natural evolutionary systems. Genetic Algorithms (GAs) are adaptive heuristic search algorithm based on the evolutionary ideas of natural selection and genetics. As such they represent an intelligent exploitation of a random search used to solve optimization problems. Although randomized, GAs are by no means random, instead they exploit historical information to direct the search into the region of better performance within the search space.

Fuzzy Logics:

Fluffy Logic was started in 1965 by Lotfi A. Zadeh, educator for software engineering at the University of California in Berkeley. Fundamentally, Fuzzy Logic (FL) is a multivalve rationale that permits middle of the road qualities to be characterized between traditional assessments such as genuine/false, yes/no, high/low, and so forth. Ideas like rather tall or quick can be defined scientifically and handled by PCs, keeping in mind the end goal to apply a more human-like state of mind in the programming of PCs. Fluffy frameworks are a different option for customary thoughts of set participation and rationale that has its starting points in antiquated Greek reasoning.

Mat Lab:

MATLAB, short for MATrix LABoratory is a programming bundle particularly intended for brisk and simple experimental counts and I/O. It has actually several inherent capacities for a wide assortment of calculations and numerous tool stashes intended for particular examination disciplines, including insights, improvement, arrangement of fractional differential comparisons, information investigation.

II. EXPERIMENTAL DESIGN METHODOLOGY

Design Of Experiment (Doe) Techniques:

The Design of an experiment is the synchronous calculation of two or more variables for their capacity to influence the resultant normal. To satisfy this in a successful and accurately appropriate form, the levels of the components are removed in an energetic method, the results specific test combinations are observed, and the complete set of results is poor depressed to focus the powerful elements and preferred levels, and whether expands or diminishes.

The DOE methodology is separated into three fundamental stages

Arranging Phase:

The arranging stage is most dynamic stage for the test to give the normal data. An experimenter will learn currently and over the data is in a positive sense and negative sense. Positive data is an ID of which variables and which levels lead to improve piece implementation. Negative data is a sign of which components don't quick change.

Conducting phase:

Conducting stage is the most supreme stage, when the test results are actually collected. On the off chance that experimenters are decently arranged and led, the dissection is really much less demanding and more horizontal to yield positive data about elements and levels.

Analysis phase:

Analysis phase is the point at which the positive data regarding the selected components and levels is produced dedicated around the past two stages. The dissection stage is minimum precarious regarding whether the trial will effectively produce positive results. These decisions are made with the help of various analytical techniques mostly used the analysis of variance (ANOVA). The advanced proposition is the collection of numerical results and numerical techniques for determining and identifying the best result from a collecting of options without demanding to clearly explain and measure all possible selections. There are different techniques for design of experiment techniques are there for design and conducting experiments. These are

1. Factorial design
2. Response surface methodology
3. Mixture design
4. Taguchi design

Response Surface Methodology Technique:

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response(output variable) which is influenced by several independent variables (input variables). An experiment is a series of tests, calledruns, in which changes are made in the input variables in order to identify the reasons for changes in the output response.

Originally, RSM was developed to model experimental responses (Box andDraper, 1987), and then migrated into the modelling of numerical experiments. The difference is in the type of error generated by the response. In physical experiments ,inaccuracy can be due, for example, to measurement errors while, in computer experiments, numerical noise is a result of incomplete convergence of iterative processes, round-off errors orthe discrete representation of continuous physical phenomena (Giunta etal., 1996;vanCampenetal., 1990, Toropov etal., 1996). In CRSM, the errors are assumed to be random.

Types of Designs in RSM Technique:

RSM design follows the four steps:

1. Full Factorial design
2. Central composite design
3. D-optimal design and
4. Box-Behnken design

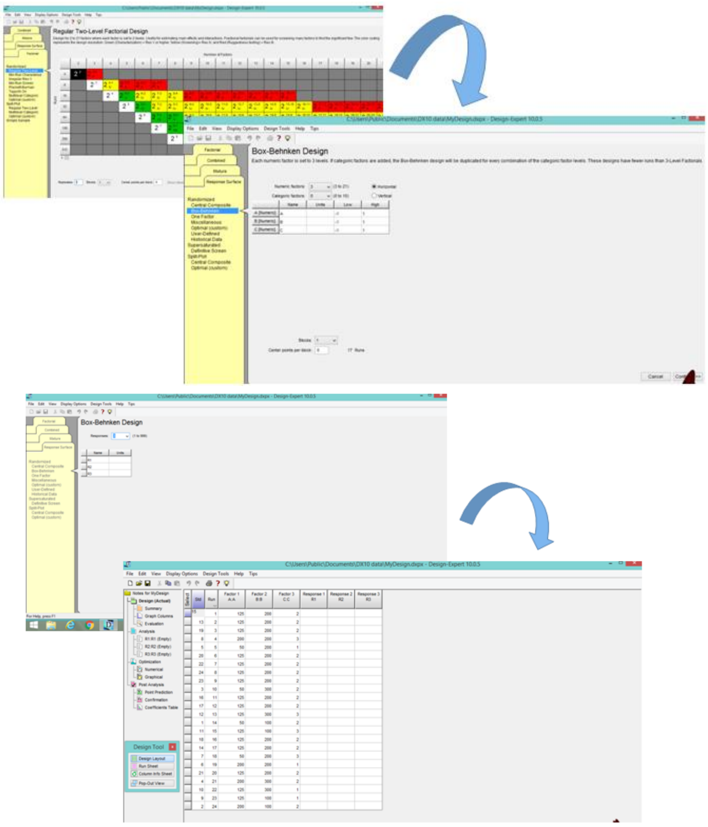


Figure 3. Screenshots of DOE in Design Expert-10 Software

Work Piece Material:

DUPLEX STAINLESS-STEEL 2205 is a Austenite-Ferrite alloy with additions of molybdenum, copper, and titanium. The alloy's chemical composition, given in Table , is designed to provide exceptional resistance to many corrosive environments. The nickel content is sufficient for resistance to chloride-ion stress-corrosion cracking. The nickel, in conjunction with the molybdenum and copper, also gives outstanding resistance to reducing environments such as those containing sulfuric and phosphoric acids. The molybdenum also aids resistance to pitting and crevice corrosion. The alloy's chromium content confers resistance to a variety of oxidizing substances such as nitric acid, nitrates and oxidizing salt. The titanium addition serves, with an appropriate heat treatment, to stabilize the alloy against sensitization to intergranular corrosion. The resistance of DUPLEX

STAINLESS-STEEL 2205 to general and localized corrosion under diverse conditions gives the alloy broad usefulness and it doesn't change it properties even it high temperature and at low temperature also due to the combination of Austenite-Ferrite alloy.

Application:

1. Chemical processing, pollution control
2. oil and gas recovery, acid production
3. pickling operations
4. Nuclear fuel reprocessing, and handling of radioactive wastes.

S.NO	Element	% of Chemical Composition
1	Carbon	0-0.03
2	Manganese	2.0
3	Chromium	21-23
4	Molybdenum	2.5-3.5
5	Copper	0.05
6	phosphorous	0-0.03
7	Nickel	4.5-6.5
8	Manganese	2.0
9	Sulfur	0-0.02
10	Silicon	1.0
11	Nitrogen	0.08-0.2

Figure 4. chemical composition of work material

Magnification:

The micro structure of DUPLEX STAINLESS STEEL-2205when seen with mag nifying lens.

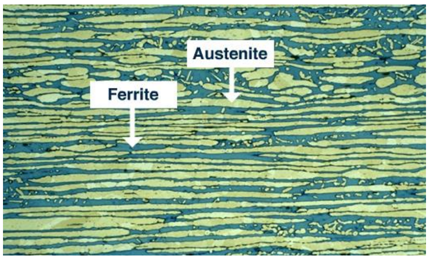


Figure 5. microstructure of duplex stainless steel-2205

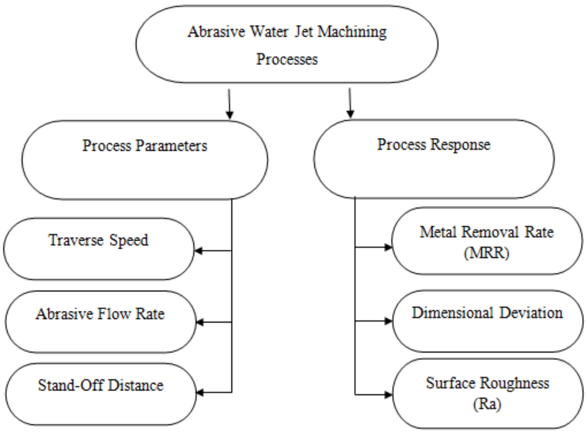


Figure 6. A Chart on Input & Output Process Parameters

Machine Details :

Table 1

Description	**Abrasive Water Jet Machining**
Controlling of Machine	CNC
Voltage	415 V
Frequency	50 Hz
Phases	3
Power	547 W
Current	1.8 A
Table size	3 * 3 * 1.5
Travel	X-axis – 3000mm, Y-axis – 3000mm, Z-axis – 260mm
Nozzle diameter	1.1 mm
Abrasive type	Garnet
Abrasive size	80 Mesh
Orifice diameter	0.35 mm
Focussing tube diameter	8 mm
Water pressure	3500 bars
Water flow rate	3.5 litre/min
Impact angle	90 degrees
Nozzle Length	80 mm

III. MEASUREMENT OF EXPERIMENTAL PARAMETERS

The discussions related to the measurement of Abrasive Water Jet Machining experimental processes parameters e.g. Metal Removal Rate (MRR) and Dimensional deviation, Surface roughness (Ra) are presented in the following subsections.

Mechanism and Evaluation of Metal Removal Rate (MRR) :

Metal Removal Rate (MRR) is the rate at which the material is removed from the work piece. The MRR is defined as the ratio of the amount of metal removed from the work piece in mm3 to time taken for machining in minutes.

MRR=((Initialweight-Finalweight)in grams)/(machining timein minutes)

Where,

Initial weight= Weight of work piece before machined.

Final weight= Weight of Work piece after machined + cutted specimens. Here we get MRR in terms of mm3/min.

Before machining:

The actual weight of the super alloy after purchasing was found out to be 1394 gm.

After machining:

The weight of the alloy (without 24 specimens) and the weight of the 24 specimens and the amount of metal removed during machining calculated from metal removal rate combinely turned out to be 1378gm which is quiet near to the original weight of the alloy DUPLEX STAINLESS STEEL-2205 i.e., 1394gm. Hence it is proven that AWJM is a precise and accurate machine.

Mechanism and Evaluation of Dimensional deviation :

Dimensional Deviation is defined as the width of the material that is removed by a cutting process

DimensionalDeviation = ((Observed value-Actual value))/((Actual Value))*100

Where,

Observed value = value of the machined specimen on the work piece.

Actual value = Value of the specimen before machining

Figure 7. Measurement of width in vernier calipers

Mechanism and Evaluation of Surface roughness (Ra):

In this work the surface roughness is measured by Mitutoyo surftest SJ-201P The surface roughness of all the 24 specimens is calculated by using Mitutoyo surftest SJ-201P instrument as shown in adjacent table

Figure 8. Mitutoyo surftest SJ-201P instrument

Table 2

S.NO	R_a	R_q	R_Z	MEAN RESPONSE VALUE
1	2.482	3.159	15.230	6.957
2	2.765	3.492	17.349	7.8686
3	2.662	3.338	16.011	7.337
4	11.483	15.536	73.151	33.339
5	3.983	5.052	23.755	10.931
6	2.962	3.657	17.751	8.1234
7	4.216	5.631	27.821	12.556
8	4.536	5.531	24.774	11.6136
9	3.713	4.522	20.207	9.4806
10	3.229	4.045	20.012	9.0953
11	3.726	4.861	21.491	10.026
12	0.853	1.122	5.712	7.687
13	3.034	3.893	18.457	8.4613
14	3.686	4.597	21.227	9.8367
15	0.976	1.299	6.912	3.0623
16	3.508	4.648	20.298	9.4846
17	4.950	6.524	32.530	14.668

18	2.299	2.868	14.173	6.4467
19	2.441	3.136	15.971	7.1826
20	3.349	4.337	19.615	9.1003
21	2.524	3.044	14.241	6.603
22	0.135	1.612	0.118	0.6216
23	2.642	3.223	14.179	6.6813
24	2.815	3.351	13.794	6.6534

IV. RESULTS AND DISCUSSION

This research analysis have been done by using Design Expert 10 software and by using the response surface methodology technique. we require to optimize process parameters for multi responses, so Response surface methodology technique is employed for optimizing process parameters to get maximizing Metal Removal Rate, minimum dimensional deviation and Surface Roughness simultaneously during Abrasive water jet machining(AWJM) process.

Table 3

STANDARD	RUN	FACTOR-1	FACTOR-2	FACTOR-3	RESPONSE-1	RESPONSE-2	RESPONSE-3
		TRANSVERSE SPEED	ABRASIVE FLOW RATE	STAND OFF DISTANCE	MRR	DIMENSIONAL DEVIATION	SURFACE ROUGHNESS
17	1	125	200	2	6.9565	-23.112	2.482
22	2	125	200	2	6.5306	-24.889	2.765
16	3	125	200	2	4.7761	-22.44	2.662
4	4	200	300	2	6.1302	-16.24	11.483
23	5	125	200	2	14.4144	-21.54	3.983
13	6	125	200	2	10.8108	-15.01	2.962
15	7	125	200	2	14.2587	-23.12	4.216
10	8	125	300	1	16.8421	-19.67	4.536
6	9	200	200	1	16.6667	-22.12	3.713
18	10	125	200	2	17.2043	-23.67	3.229
12	11	125	300	3	14.9953	-15.45	3.726
14	12	125	200	2	19.2771	-22.12	0.853
21	13	125	200	2	23.5294	-20.45	3.034
20	14	125	200	2	18.6046	-20.67	3.686
5	15	50	200	1	18.1818	-21.89	0.976
9	16	125	100	1	21.9178	-22.56	3.508
8	17	200	200	3	24.6153	-22.48	4.95
11	18	125	100	3	26.6771	-23.67	2.299
7	19	50	200	3	23.8805	-24.01	2.441
24	20	125	200	2	22.8571	-23.34	3.349
3	21	50	300	2	21.6216	-21.89	2.524
19	22	125	200	2	23.5294	-22	1.978
2	23	200	100	2	28.0701	-24.24	2.642
1	24	50	100	2	25.2018	26.23	2.815

RESPONSE REPORT ON OUTPUT PARAMETERS :

For three output parameters:

1 : METAL REMOVAL RATE

2 : DIMENSIONAL DEVIATION

3 : SURFACE ROUGHNESS

RESPONSE-1 METAL REMOVAL RATE (MRR) TRANSFORM : NONE

Summary (detailed tables are shown below)

Table 4

	Sequential	Lack of Fit	Adjusted	Predicted	
Source	**p-value**	**p-value**	**R-Squared**	**R-Squared**	
Linear	0.1051	0.6771	0.1478	0.0098	Suggested
2FI	0.5240	0.6278	0.1180	-0.1270	
Quadratic	0.2877	0.8225	0.1744	-0.1666	
Cubic	0.8225		0.0295		Aliased

Final report on MRR :

Table 5

Factor	Coefficient Estimate	Df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	17.81	1	1.29	15.12	20.51	
A-Transverse Speed	-1.68	1	2.24	-6.34	2.99	1.00
B-Abrasive flow rate	-5.28	1	2.24	-9.95	-0.62	1.00
C-Stand off Distance	2.07	1	2.24	-2.60	6.74	1.00

Final Equation in Terms of Coded Factors:

MRR = +17.81 -1.68*A -5.28*B +2.07*C

Final Equation in Terms of Actual Factors:

MRR = +27.03638 -0.022339* Transverse Speed -0.052847* Abrasive flow rate +2.06998* Stand off Distance

RESPONSE-2 DIMENSIONAL DEVIATION TRANSFORM: NONE

Summary (detailed tables shown below)

Table 6

Source	**Sequential**	**Lack of Fit**	**Adjusted**	**Predicted**	
	p-value	**p-value**	**R-Squared**	**R-Squared**	
Linear	0.3588	< 0.0001	0.0173	-0.6530	
2FI	0.0320	< 0.0001	0.3017	-1.2537	
Quadratic	0.0341	< 0.0001	0.5342	-3.1044	Suggested
Cubic	< 0.0001		0.9389		Aliased

Final Report:

Table 7

Factor	Coefficient Estimate	Df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	-21.86	1	1.99	-26.14	-17.59	
A-Transverse Speed	-5.44	1	2.44	-10.67	-0.21	1.00
B-Abrasive flow rate	-3.63	1	2.44	-8.86	1.61	1.00
C-Stand off Distance	0.079	1	2.44	-5.15	5.31	1.00
AB	14.03	1	3.45	6.63	21.43	1.00
AC	0.44	1	3.45	-6.96	7.84	1.00
BC	1.33	1	3.45	-6.07	8.73	1.00
A^2	5.27	1	3.15	-1.48	12.03	1.11
B^2	7.56	1	3.15	0.80	14.31	1.11
C^2	-6.03	1	3.15	-12.79	0.72	1.11

Final Equation in Terms of Coded Factors:

Dimensional deviation = -21.86 -5.44 *A -3.63*B +0.079 *C +14.03 *AB +0.44 *AC +1.33 *BC +5.27 *A^2 +7.56*B^2 -6.03*C^2

RESPONSE-3 SURFACE ROUGHNESS

ANOVA for Response Surface Quadratic model

Analysis of variance table [Partial sum of squares - Type III]

Table 8

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	72.53	9	8.06	6.22	0.0013	Significant
A-Transverse Speed	24.61	1	24.61	19.01	0.0007	
B-Abrasive flow rate	15.14	1	15.14	11.69	0.0041	
C-Stand off Distance	0.058	1	0.058	0.045	0.8350	
AB	20.85	1	20.85	16.10	0.0013	
AC	0.013	1	0.013	0.010	0.9216	
BC	0.040	1	0.040	0.031	0.8633	
A^2	2.47	1	2.47	1.91	0.1886	
B^2	7.09	1	7.09	5.47	0.0347	
C^2	1.91	1	1.91	1.48	0.2445	
Residual	18.13	14	1.29			
Lack of Fit	9.00	3	3.00	3.61	0.0491	Significant
Pure Error	9.13	11	0.83			
Cor Total	90.65	23				

Final Equation in Terms of Actual Factors:

Surface roughness =+9.23667-0.067873*Transverse Speed -0.074889 * Abrasive flow rate +2.50487 * standoff Distance +3.04400E-004* Transverse Speed * Abrasive flow rate-7.60000E-004* Transverse Speed * Stand off

Distance+9.97500E-004* Abrasive flow rate * Stand off Distance+1.27600E-004* Transverse Speed^2+1.21500E-004* Abrasive flow rate^2-0.63100* Stand off Distance^2

Final Report of surface roughness :

Table 9

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	2.93	1	0.33	2.23	3.64	
A-Transverse Speed	1.75	1	0.40	0.89	2.62	1.00
B-Abrasive flow rate	1.38	1	0.40	0.51	2.24	1.00
C-Stand off Distance	0.085	1	0.40	-0.78	0.95	1.00
AB	2.28	1	0.57	1.06	3.50	1.00
AC	-0.057	1	0.57	-1.28	1.16	1.00
BC	0.100	1	0.57	-1.12	1.32	1.00
A^2	0.72	1	0.52	-0.40	1.83	1.11
B^2	1.22	1	0.52	0.10	2.33	1.11
C^2	-0.63	1	0.52	-1.74	0.48	1.11

Final Equation in Terms of Coded Factors:

Surface roughness = +2.93+1.75*A+1.38*B+0.085*C+2.28*AB0.057*AC+0.100*BC+0.72*A^2+1.22*B^2-0.63*C^2

MEAN, MEDIAN, DEVIATION W.R.TO TRANSVERSE SPEED :

Table 10

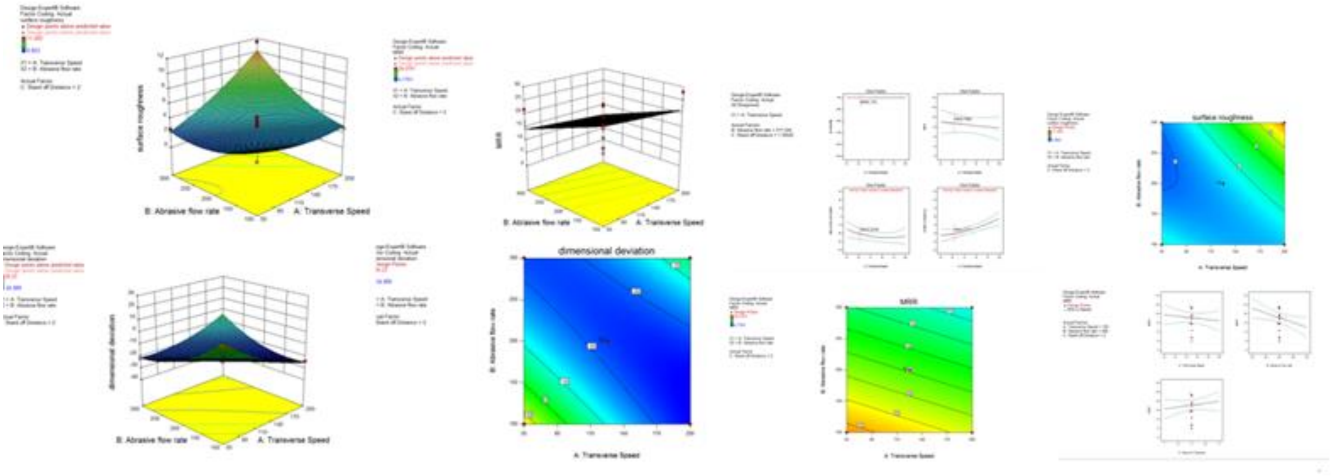
	Predicted	Predicted				CI for Mean		99% of Population	
Response	**Mean**	**Median[1]**	**Observed**	**Std Dev**	**SE Mean**	**95% CI low**	**95% CI high**	**95% TI low**	**95% TI high**
MRR	17.8146	17.8146	-	6.33145	1.2924	15.1187	20.5105	-6.55583	42.1849
dimensional deviation	-21.8634	-21.8634	-	6.8998	1.9918	-26.1354	-17.5914	-51.3142	7.58739
surface roughness	2.93325	2.93325	-	1.13788	0.328478	2.22873	3.63777	-1.92364	7.79014

MEAN ,MERDIAN ,DEVIATION FOR ABRASIVE FLOW RATE :

Table 11

	Predicted	Predicted				CI for Mean		99% of Population	
Response	**Mean**	**Median[1]**	**Observed**	**Std Dev**	**SE Mean**	**95% CI low**	**95% CI high**	**95% TI low**	**95% TI high**
MRR	15.959	15.959	-	6.33145	2.31909	11.1215	20.7966	-10.1821	42.1002
dimensional deviation	-23.1369	-23.1369	-	6.8998	3.03968	-29.6564	-16.6174	-54.4334	8.15954
surface roughness	4.02686	4.02686	-	1.13788	0.50129	2.9517	5.10202	-1.13441	9.18812

GRAPHS :



V. CONCLUSION

In this present analysis of various parameters and on the basis of experimental results, analysis of variance (ANOVA) the following conclusions can be drawn for effective machining of DUPLEX STAINLESS STEEL-2205 by AWJM process as follows:

Traverse Speed (TS) is the most significant factor on MRR during AWJM. Meanwhile Abrasive Flow Rate and Standoff distance is sub-significant in influencing. In case of surface Roughness Abrasive Flow Rate is most significant control factor.

In case of Metal Remove Rate (MRR) & Surface Roughness Transverse speed & Abrasive Flow Rate are most significant control factors.

The optimal condition for maximizing Metal Removal Rate, minimum dimensional deviation and Surface roughness simultaneously in Abrasive Water Jet Machining (AWJM) process, is found to be i.e.

- ✓ Transverse speed is 125 mm/min,
- ✓ Abrasive Flow Rate is 200 gm/min and
- ✓ Stand off Distance is 2 mm.

VI. REFERENCES

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