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Optimization of Machining Parameters in AWJM Process for an Copper Iron Alloy Using RSM and Regression Analysis

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Abstract: *For the past several years, we have noticed a quick growth in cutting of hard metals and alloys using unconventional machining process. Abrasive water jet cutting is the most recently developed unconventional machining process in cutting different kinds of hard materials these days. The principle in which this process works is based on the principle of a narrow, focused, water jet mixed with abrasive particles resulting in very high velocity that when it impacts on the work piece removes the surface of the metal. Machine economics and quality of machining are determined by the machining parameters. In this study the effect of five process parameters on MRR and SR of the element named Copper Iron alloy which is cut by abrasive waterjet cutting machine was experimentally done and analysed. Based on the Response Surface Methodology, different sets of experiments were conducted on this element by varying the water pressure, abrasive flow rate, orifice diameter, focusing nozzle diameter and standoff distance. In this paper all the effects of process parameters on MRR and SR has been studied based on the experimental results and useful recommendations have been given in order to select the suitable process parameters in abrasive waterjet cutting of copper iron alloy and a predictive model for MRR and SR is developed for this copper iron alloy using regression analysis is presented in this paper. It is found that water pressure, abrasive flow rate, orifice diameter, nozzle diameter and standoff distance and along with their interactions have significant effect on the MRR and SR.*

Keywords: *Abrasive Water jet Machining, American Element, Response Surface Methodology, Regression Analysis, Material Removal Rate, Surface Roughness*

1. Introduction

The reviews of such past studies have prominent decision variables, objective functions, constraints, variable bounds, remarks and their limitation. The results were recapitulated as follows. Abrasive waterjet cutting is one of the newly developed processes by which different types of brittle materials like glass, ceramics and stones, composite materials, ferrous and non-ferrous materials are machined. According to the research from Hascalik A., Caydas U. and Gurun H. Abrasive Waterjet Cutting is a rapidly developing technology that is used in industry for a number of applications as well as plate profile cutting and machining of a range of materials [1]. Based on the paper given by Momber and Kovacevic (1992), the AWJM is less sensitive to material properties as it has no thermal effects, impose minimal stresses on the workpiece, and has high machining versatility and high flexibility [2]. Based on the paper given by Hashish M., a flow of small abrasive particles is introduced in the waterjet and the key role of water is to speed up large quantities of abrasive particles to a high velocity to produce a high coherent jet. This jet is then impacted towards the working surface [3].

R. Kovacevic, M. Fang made few attempts have been made to model and optimize the process parameters in AWJC. The approaches employed in this direction include Design of Experiments (DOE), Regression Modeling, Analysis of Variance (ANOVA), Fuzzy Logics and Artificial Neural Networks. Some of these studies gave rise to various mathematical equations developed for predicting the output parameters [4]. Hashish was the first who developed a set of mathematical model to relate the process parameters settings to the process output variables in water jet technique [5]. Later

Ramulu and Arola used regression analysis to predict depth of cut and deformation wear for graphite/epoxy composite materials [6].

Some of the advantages of AWJC are no thermal distortion, high machining versatility, minimum stresses on the work piece, high flexibility and small cutting forces. It is of better-quality when compared to other cutting techniques in processing variety of materials and widely used in industry [7]. Some of the limitations of AWJC are. It generates loud noise, a messy functioning surroundings, creates tapered edges on the kerf, when cutting at high cutting speeds [8]. According to the research from C Ma, R T Deam the chosen material is acrylic and the mechanisms underlying the formation of the kerf profile are discussed and the optimal speed for achieving the straightest cutting edge is presented in this paper [9].

The performance measures considered in this paper are MRR and SR is considered as in many industrial application is the main constraint on the process applicability. In order to control and optimize the AWJC process effectively, predictive models for depth of cut have been previously developed for, titanium aluminum, mild steel, copper, brass, ceramics etc. [12], [13], [14] and [15] from the research of Chithirai Pon Selvan M. and Mohanasundara Raju N. But no such models of Material Removal Rate and Surface Roughness have been developed for Copper iron alloy. This paper assesses the influence of abrasive waterjet cutting process parameters on MRR and SR of Copper iron alloy. An empirical model for the prediction of MRR and SR in AWJC process of Copper iron alloy is developed using RSM and optimized using regression analysis is also presented in this paper.

2. EXPERIMENTAL WORK

2.1 Material

The origin of the word copper comes from the Latin word cuprium which translates as metal of Cyprus, a Mediterranean island, was known as an ancient source of mined copper. Copper iron alloy is used as a building material, a conductor of heat and electricity, and as a component of various metal alloys. Due to its high electrical conductivity, large amounts of copper are used by the electrical industry for wire. Since copper is resistant to corrosion caused by moisture, it is widely used in pipes, coins, and jewelry. Copper is often too soft for its applications, so it is incorporated in numerous alloys. This alloy is available as bar, ingot, ribbon, wire, shot, sheet and foil. Ultra high purity and high purity forms also include metal powder, submicron powder, nano-scale, targets for thin film deposition, and pellets for Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD) applications. It has excellent corrosion resistance to atmospheric conditions. The main composition of this alloy is 96% copper and 4% iron. Its density is 8.87285g/cm^3. The dimension of this Copper Iron alloy plate used for this study is 150mm x 50mm x 50mm shown in figure 1.

Figure 1. *This Copper Iron alloy Specimen (150mm x 50mm x 50mm)*

3. RESPONSE SURFACE 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 which were shown in Table 1 and the commonly used constant parameters of AWJM and the nomenclature used is shown in Table 2 and Table 3. In Response surface design, a Box-Behnken design table with 46 experiments was selected. The parameters and levels were selected according to the review of some journals that has been recognized on AWJC on Aluminium [13] Mild Steel [14] Alumina Ceramics [10] [19] Graphite [6] and Epoxy Composite Laminate [20].

Table 1. *Levels of Parameters Used in Experiment*

Levels	**Water Pressure (P) Bar**	**Abrasive Flow Rate (m_f) Kg/m^3**	**Orifice Diameter (d_o) mm**	**Focusing Nozzle Diameter (d_f) mm**	**SOD (s) mm**
Low	3400	0.4	0.3	0.9	1
Intermediate	3600	0.55	0.33	0.99	2
High	3800	0.7	0.35	1.05	3

Table 2. *Constant Parameters*

Sl. No	**Parameters**	**Type / Value**
1.	Jet impact angle	Neutral nozzle position (90°)
2.	Nozzle length	76.2 mm
3.	Size of abrasive material	80 mesh garnet
4.	Type of abrasive material	Hard rock
5.	Diameter of abrasive particles	0.18mm
6.	Density of garnet particles	4100 kg/m^3
7.	Composition of garnet	36% FeO, 33% SiO_2, 20% $Al2O_3$, 4%MgO, 3% TiO_2, 2% CaO and 2% MnO_2

Table 3. *Nomenclature*

Sl. No.	**Parameters**	**Symbol**	**Unit**
1.	Water Pressure	P	Bar
2.	Abrasive Flow Rate	m_f	Kg/min
3.	Orifice Diameter	d_o	mm
4.	Focusing Nozzle Diameter	d_f	mm
5.	Stand Off Distance	S	mm
6.	Material Removal Rate	MRR	mm^3/min
7.	Surface Roughness	SR	µm

4. DATA COLLECTION AND EXPERIMENTATION

The cutting parameters are set to the pre-defined levels for all the experiments. Forty six experiments were conducted in this element named Copper iron alloy as per the Box-Behnken design considered. The machine or the equipment used to cut the copper iron alloy was the abrasive waterjet cutting machine which is equipped with KMT ultrahigh pressure pump with the designed pressure of 4000 bar is shown in figure 2. The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve and a work piece table. Through the use of controller fixed in the control stand, SOD is adjusted for different experiments. The abrasive waterjet system programmed by numerical control code is used to adjust the transverse speed and control the supplement of abrasives.

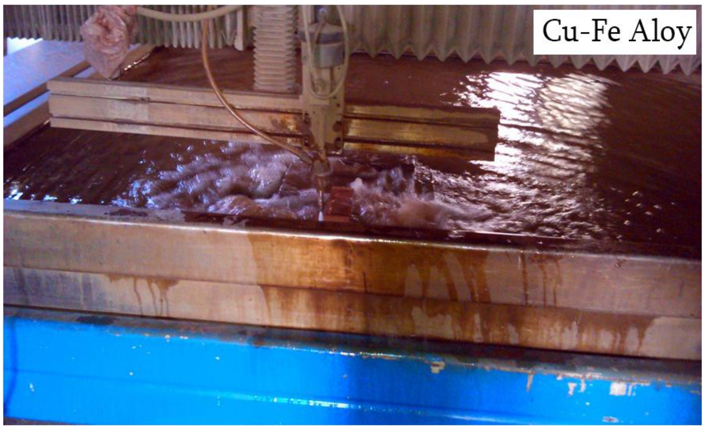

Figure 2. *Abrasive Waterjet System Experiment in Under Way*

Water is pumped at a very high pressure about 2000-4000 bar using intensifier. When water at such pressure is issued through the orifice of about 0.2 – 0.4 mm diameter, converts the potential energy of water into kinetic energy, resulting a very high velocity jet of 1000 m/s. This high velocity of water jet when it comes out of the nozzle cuts the materials of the required size and a shape is shown in figure 3.

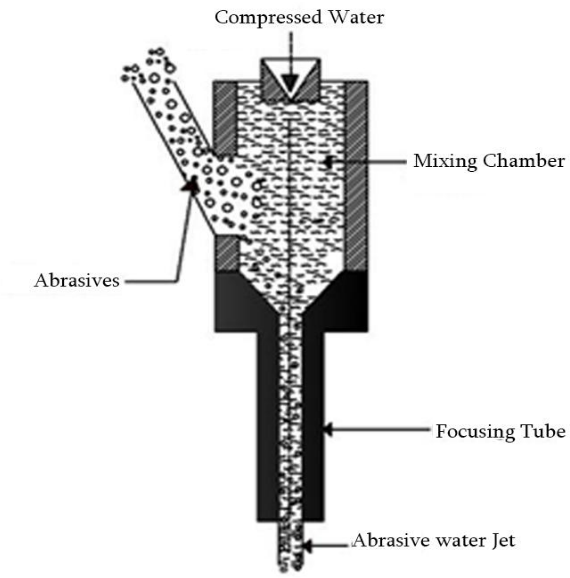

Figure 3. *AWJC Mixing Chamber*

5. Experimental Investigations

In Design of Experiments, Based on Response surface methodology, Box-behnken design for five factors with 46 experiments is selected and done experimentally and machining time is found for each experiment. The material removal rate is calculated experimentally using the following formula;

MRR = (Initial Weight - Final Weight) / Machining Time

Portable surface roughness tester is used to measure the surface roughness of copper iron alloy shown in figure 4.

Figure 4. *Portable Surface Roughness Tester*

Table 4. *Scheduling Matrix of the Experiments with the Optimal Model Data*

Sl. No	Pressure (Bar)	Abrasive Flow Rate (Kg/min)	Orifice Diameter (mm)	Focusing Tube Diameter (mm)	Stand Off Distance (mm)	MRR mm^3/min	SR (μm)
1.	3400	0.55	0.33	0.99	3	897.80	3.62
2.	3600	0.55	0.33	0.9	1	1000.03	1.63
3.	3600	0.55	0.3	1.05	2	961.93	2.24
4.	3600	0.55	0.33	0.9	3	918.21	3.09
5.	3800	0.55	0.33	0.9	2	1043.96	1.767
6.	3600	0.55	0.33	0.99	2	928.76	2.228
7.	3400	0.4	0.33	0.99	2	762.29	3.309
8.	3600	0.7	0.35	0.99	2	985.39	2.19
9.	3800	0.55	0.33	0.99	3	987.80	1.901
10.	3800	0.55	0.3	0.99	2	1025.41	1.66
11.	3600	0.55	0.33	0.99	3	907.89	2.77
12.	3400	0.55	0.33	1.05	2	800.02	2.991
13.	3600	0.4	0.33	0.99	1	920.30	1.989
14.	3600	0.55	0.33	0.99	2	922.40	2.224
15.	3600	0.55	0.35	0.9	2	948.38	2.43
16.	3600	0.55	0.3	0.9	2	950.62	2.32
17.	3400	0.55	0.33	0.9	2	817.84	2.83
18.	3600	0.55	0.33	0.99	2	897.80	2.29
19.	3600	0.4	0.3	0.99	2	827.89	2.589
20.	3400	0.55	0.35	0.99	2	814.54	3.19
21.	3800	0.4	0.33	0.99	2	961.93	1.799
22.	3600	0.7	0.33	0.99	3	997.56	2.357
23.	3600	0.7	0.33	0.99	1	987.80	1.50
24.	3600	0.4	0.35	0.99	2	846.98	2.70
25.	3600	0.4	0.33	0.9	2	863.27	2.79
26.	3600	0.55	0.35	0.99	3	928.76	3.03
27.	3600	0.7	0.33	0.9	2	973.52	1.85
28.	3400	0.55	0.33	0.99	1	792.18	2.24
29.	3600	0.7	0.3	0.99	2	973.52	1.734
30.	3600	0.55	0.33	1.05	1	957.37	2.00
31.	3600	0.55	0.3	0.99	1	990.22	1.66

32.	3800	0.7	0.33	0.99	2	1100.85	1.407
33.	3600	0.4	0.33	1.05	2	824.51	2.47
34.	3600	0.55	0.3	0.99	3	939.56	2.80
35.	3600	0.55	0.33	0.99	2	922.40	2.201
36.	3800	0.55	0.33	1.05	2	1035.93	1.564
37.	3400	0.7	0.33	0.99	2	831.30	2.456
38.	3600	0.55	0.35	1.05	2	907.89	2.56
39.	3400	0.55	0.3	0.99	2	833.01	2.80
40.	3600	0.4	0.33	0.99	3	824.51	3.01
41.	3600	0.55	0.33	0.99	2	928.76	2.23
42.	3600	0.55	0.35	0.99	1	968.85	2.00
43.	3800	0.55	0.35	0.99	2	1049.38	1.863
44.	3600	0.7	0.33	1.05	2	961.93	1.99
45.	3600	0.55	0.33	1.05	3	922.40	2.65
46.	3800	0.55	0.33	0.99	1	1138.06	1.35

6. MATHEMATICAL MODELING

Response Surface Methodology (RSM) is a method of design of experiments which are helpful for modeling is a collection of mathematical and statistical techniques by which the correlation between the response and the variables are found out. It is an empirical modelization technique committed to the assessment of relations existing between a group of controlled experimental factors and the observed results of one or more selected criteria. To achieve a sensible model a knowledge of RSM is very essential. Only five experimental factors which are capable of influencing the studied process yield are Pressure, Abrasive flow rate, Orifice diameter, Focusing nozzle diameter and Stand off distance. The table 5 shows the steps involved in the mathematical modeling.

Table 5. *Steps Involved in Mathematical Modelling*

Step	Process
First	Describe the limits of the experimental domain to be explored. The parameters which are selected for my research work are pressure, abrasive flow rate, orifice diameter, focusing nozzle diameter, standoff distance. The levels of each parameter are shown in table 1.
Second	Scheduling to achieve the experiments using RSM of Box Behnken design which gives a reasonably accurate prediction for all five parameters and from the design 46 experiments were conducted with the mixture of input parameters is shown in table 4. With the minimum number of experiments the prediction model for MRR and SR is good is the advantage of RSM.
Third	The mathematical model is then developed which demonstrate the relationship between pressure, abrasive flow rate, orifice diameter, focusing nozzle diameter, standoff distance, material removal rate and surface roughness i.e., process variables and response.
Fourth	Analysis of Variance for the capability of the model is then performed in this step. The F ratio is calculated for 95% level of confidence. The value which are less than 0.05 are considered significant and the values greater than 0.05 are not significant and the model is adequate to represent the relationship among machining response and the machining parameters. AWJM process is non-linear in nature the linear polynomial will be not able to predict the response accurately therefore quadratic model is used.

It is seen from the adequacy test by ANOVA those linear terms P, m_f, d_o, d_f and s, interaction terms $P\times m_f$, Pxd_o, Pxd_f, Pxs, m_fxd_o, m_fxd_f, m_fxs, d_oxd_f, d_oxs, d_f xs and square terms P^2, m_f^2, d_o^2, d_f^2, s^2. Table 6 and 9 shows the levels of significant. The fit outline suggested that the quadratic model is statistically significant for analysis of MRR and SR. The quadratic model for MRR and SR results indicate that the model is significant (R_2 and adjusted R_2 are 98.5% and 97.3% for MRR and 99.7% and 99.4% for SR respectively), and lack of fit is no significant (p-value is less than 0.05). The final response equation for MRR and SR is given as follows

MRR = 3808.07 - 0.965684 A - 1542.90 B - 13292.1 C - 621.554 D + 718.689 E + 0.000135908 A*A - 679.682 B*B + 16371.4 C*C + 610.730 D*D + 27.3263 E*E + 0.582583 A*B + 2.27099 A*C + 0.122252 A*D - 0.319850 A*E - 955.417 B*C + 571.784 B*D + 175.917 B*E - 5427.25 C*D + 111.636 C*E + 170.187 D*E

SR = 30.3516 + 0.00223958 A - 32.1430 B - 138.754 C - 6.66011 D + 7.38615 E + 5.24367E-07 A*A - 1.31594 B*B + 221.213 C*C + 9.85236 D*D + 0.0285801 E*E + 0.00384167 A*B - 0.00987783 A*C - 0.00605543 A*D - 0.00103625 A*E + 23.5694 B*C + 10.5488 B*D - 0.273333 B*E + 26.1778 C*D -1.42747 C*E - 2.68095 D*E

The values of MRR and SR With design matrix are tabulated in table 4 after the 46 experiments have been conducted experimentally. The inspection of goodness of fit of the model is very much necessary after the analysis of data. The model sufficiency scrutiny include the test for significance of the regression model, test for significance on model coefficients, and test for lack of fit. For this purpose, ANOVA performed. The fit outline suggested that the quadratic model is statistically significant for analysis of MRR and SR.

Table 6. *ANOVA Table Estimated Regression Coefficients for Material Removal Rate*

Term	Coef	SECoef	T	P
Constant	920.080	6.257	147.037	0.000
A	110.165	3.673	29.996	0.000
B	60.834	3.673	16.564	0.000
C	-1.722	3.527	-0.488	0.630
D	-7.463	3.527	-2.116	0.044
E	-24.495	3.599	-6.806	0.000
A*A	5.432	4.689	1.158	0.258
B*B	-15.291	4.689	-3.261	0.003
C*C	10.234	4.935	2.074	0.049
D*D	3.436	4.935	0.696	0.493
E*E	27.322	4.740	5.764	0.000
A*B	17.476	6.772	2.581	0.016
A*C	11.355	6.673	1.702	0.101
A*D	1.832	6.673	0.275	0.786
A*E	-63.955	6.772	-9.444	0.000
B*C	-3.584	6.673	-0.537	0.596
B*D	6.432	6.673	0.964	0.344
B*E	26.387	6.772	3.896	0.001
C*D	-10.179	6.575	-1.548	0.134
C*E	2.791	6.671	0.418	0.679
D*E	12.764	6.671	1.913	0.067
S = 13.54 R-Sq = 98.5% R-Sq(adj) = 97.3%				

Table 7. *Analysis of Variance for Material Removal Rate*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	20	13.3691	13.3691	0.66845	394.7	0.0
Linear	5	12.6245	11.2100	2.24200	1323	0.0
Square	5	0.1983	0.1971	0.03942	23.28	0.0
Interaction	10	0.5463	0.5463	0.05463	32.26	0.0
Residual Error	25	0.0423	0.0423	0.00169		
Lack-of-Fit	21	0.0380	0.0380	0.00181	1.65	0.3
Pure Error	4	0.0044	0.0044	0.00109		
Total	45	13.4114				

Table 8. *Comparison between the Predicted and the Modeling Values of Material Removal Rate*

Sl. No	Pressure (Bar)	Abrasive Flow Rate (Kg/min)	Orifice Diameter (mm)	Focusing Tube Diameter (mm)	StandOff Distance (mm)	MRR (mm^3/min) Modeling Value	MRR (mm^3/min) Experimental Value	Error	Max Error
1.	3400	0.55	0.33	0.99	3	880.9311775	897.80	1.878906494	2.87923
2.	3600	0.55	0.33	0.9	1	997.1180495	1000.03	0.291186314	
3.	3600	0.55	0.3	1.05	2	938.190605	961.93	2.467892154	
4.	3600	0.55	0.33	0.9	3	923.7115095	918.21	0.599155912	
5.	3800	0.55	0.33	0.9	2	1049.13035	1043.96	0.495263181	
6.	3600	0.55	0.33	0.99	2	918.3910835	928.76	1.116425826	
7.	3400	0.4	0.33	0.99	2	751.80179	762.29	1.375881882	
8.	3600	0.7	0.35	0.99	2	968.452783	985.39	1.718833863	
9.	3800	0.55	0.33	0.99	3	978.6033495	987.80	0.931023537	
10.	3800	0.55	0.3	0.99	2	1037.339715	1025.41	1.16340927	
11.	3600	0.55	0.33	0.99	3	924.3309435	907.89	1.810895979	
12.	3400	0.55	0.33	1.05	2	805.2525995	800.02	0.654058586	
13.	3600	0.4	0.33	0.99	1	916.794356	920.30	0.380924047	
14.	3600	0.55	0.33	0.99	2	918.3910835	922.40	0.434618007	
15.	3600	0.55	0.35	0.9	2	949.6741525	948.38	0.136459278	
16.	3600	0.55	0.3	0.9	2	932.76707	950.62	1.878030128	
17.	3400	0.55	0.33	0.9	2	827.9192495	817.84	1.232423151	
18.	3600	0.55	0.33	0.99	2	918.3910835	897.80	2.293504511	
19.	3600	0.4	0.3	0.99	2	851.726855	827.89	2.879229729	
20.	3400	0.55	0.35	0.99	2	808.7539805	814.54	0.710341972	
21.	3800	0.4	0.33	0.99	2	942.458982	961.93	2.024161633	
22.	3600	0.7	0.33	0.99	3	996.829821	997.56	0.073196499	
23.	3600	0.7	0.33	0.99	1	986.827601	987.80	0.098440879	
24.	3600	0.4	0.35	0.99	2	851.37694	846.98	0.519131503	
25.	3600	0.4	0.33	0.9	2	864.110546	863.27	0.097367683	
26.	3600	0.55	0.35	0.99	3	933.3802865	928.76	0.497468291	
27.	3600	0.7	0.33	0.9	2	971.480723	973.52	0.209474587	
28.	3400	0.55	0.33	0.99	1	795.7640575	792.18	0.452429688	
29.	3600	0.7	0.3	0.99	2	983.133953	973.52	0.987545505	
30.	3600	0.55	0.33	1.05	1	952.5909095	957.37	0.499189498	
31.	3600	0.55	0.3	0.99	1	984.785069	990.22	0.54886096	
32.	3800	0.7	0.33	0.99	2	1100.222307	1100.85	0.05701894	
33.	3600	0.4	0.33	1.05	2	832.246316	824.51	0.938292562	
34.	3600	0.55	0.3	0.99	3	935.314029	939.56	0.451910575	
35.	3600	0.55	0.33	0.99	2	918.3910835	922.40	0.434618007	

36.	3800	0.55	0.33	1.05	2	1033.79882	1035.93	0.205726304	
37.	3400	0.7	0.33	0.99	2	839.655155	831.30	1.005070973	
38.	3600	0.55	0.35	1.05	2	914.3933125	907.89	0.716310621	
39.	3400	0.55	0.3	0.99	2	838.979423	833.01	0.716608804	
40.	3600	0.4	0.33	0.99	3	821.246376	824.51	0.395825884	
41.	3600	0.55	0.33	0.99	2	918.3910835	928.76	1.116425826	
42.	3600	0.55	0.35	0.99	1	971.6877265	968.85	0.292896372	
43.	3800	0.55	0.35	0.99	2	1052.534073	1049.38	0.300565334	
44.	3600	0.7	0.33	1.05	2	965.346773	961.93	0.355199755	
45.	3600	0.55	0.33	1.05	3	930.2404695	922.40	0.850007535	
46.	3800	0.55	0.33	0.99	1	1149.31623	1138.06	0.98907171	

The predicted values and the experimental values of Material Removal Rate are compared with each other and graphically shown in the figure 5.

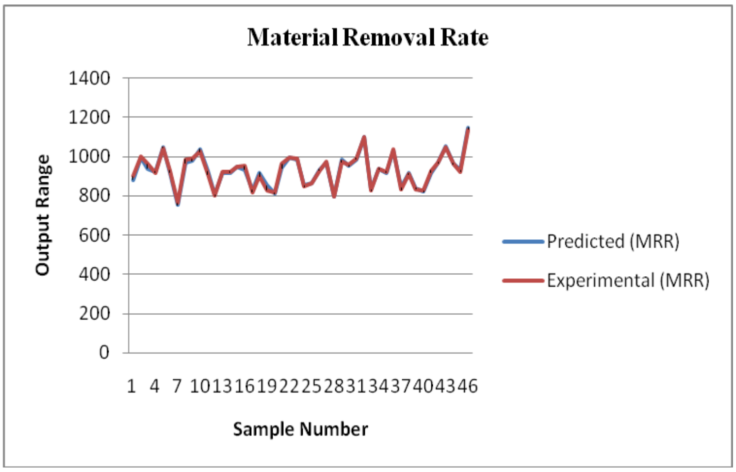

Figure 5. *Predicted Values and the Experimental Values of Material Removal Rate*

Table 9. *ANOVA Table Estimated Regression Coefficients for Surface Roughness*

Term	Coefficient	SE Coef	T	P
Constant	2.20499	0.01901	115.975	0.000
A	-0.61178	0.01116	-54.824	0.000
B	-0.35431	0.01116	-31.751	0.000
C	0.12764	0.01072	11.911	0.000
D	-0.02249	0.01072	-2.099	0.046
E	0.54178	0.01094	49.544	0.000
A*A	0.02097	0.01425	1.472	0.153
B*B	-0.02961	0.01425	-2.078	0.048
C*C	0.13826	0.01499	9.221	0.000
D*D	0.05542	0.01499	3.696	0.001
E*E	0.02858	0.01440	1.984	0.058
A*B	0.11525	0.02058	5.601	0.000
A*C	-0.04939	0.02028	-2.436	0.022
A*D	-0.09083	0.02028	-4.480	0.000
A*E	-0.20725	0.02058	-10.072	0.000
B*C	0.08839	0.02028	4.359	0.000
B*D	0.11867	0.02028	5.853	0.000
B*E	-0.04100	0.02058	-1.993	0.057
C*D	0.04908	0.01998	2.457	0.021
C*E	-0.03569	0.02027	-1.761	0.091
D*E	-0.20107	0.02027	-9.920	0.000
S = 0.04115 R-Sq = 99.7% R-Sq(adj) = 99.4%				

Table 10. *Analysis of Variance for Surface Roughness*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	20	13.3691	9.51	0.47	615.48	0.000
Linear	5	8.21	7.21	1.44	1865.63	0.000
Square	5	0.92	0.92	0.18	240.04	0.000
Interaction	10	0.37	0.37	0.03	48.48	0.000
Residual Error	25	0.01	0.01	0.00		
Lack-of-Fit	21	0.01	0.01	0.00	6.89	0.037
Pure Error	4	0.00	0.00	0.00		
Total	45	9.53				

Table 11. *Comparison between the Predicted and the Experimental values of Surface Roughness*

Sl. No	Pressure (Bar)	Abrasive Flow Rate (Kg/min)	Orifice Diameter (mm)	Focusing Tube Diameter (mm)	Stand Off Distance (mm)	SR (μm) Modeling Value	SR (μm) Experimental Value	Error	Max Error
1.	340	0.55	0.33	0.99	3	3.626877	3.62	0.1899	2.872541975
2.	360	0.55	0.33	0.9	1	1.597087	1.63	2.0191	
3.	360	0.55	0.3	1.05	2	2.199535	2.24	1.8064	
4.	360	0.55	0.33	0.9	3	3.068522	3.09	0.6950	
5.	380	0.55	0.33	0.9	2	1.794373	1.767	1.5491	
6.	360	0.55	0.33	0.99	2	2.235817	2.228	0.3508	
7.	340	0.4	0.33	0.99	2	3.295153	3.309	0.4184	
8.	360	0.7	0.35	0.99	2	2.206718	2.19	0.7634	
9.	380	0.55	0.33	0.99	3	1.932729	1.901	1.6691	
10.	380	0.55	0.3	0.99	2	1.644007	1.66	0.9634	
11.	360	0.55	0.33	0.99	3	2.758829	2.77	0.4032	
12.	340	0.55	0.33	1.05	2	3.012347	2.991	0.7137	
13.	360	0.4	0.33	0.99	1	2.012253	1.989	1.1690	
14.	360	0.55	0.33	0.99	2	2.235817	2.224	0.5313	
15.	360	0.55	0.35	0.9	2	2.499802	2.43	2.8725	
16.	360	0.55	0.3	0.9	2	2.342677	2.32	0.9774	
17.	340	0.55	0.33	0.9	2	2.856025	2.83	0.9196	
18.	360	0.55	0.33	0.99	2	2.235817	2.29	2.3660	
19.	360	0.4	0.3	0.99	2	2.592939	2.589	0.1521	
20.	340	0.55	0.35	0.99	2	3.178825	3.19	0.3503	
21.	380	0.4	0.33	0.99	2	1.785005	1.799	0.7779	
22.	360	0.7	0.33	0.99	3	2.375324	2.357	0.7774	
23.	360	0.7	0.33	0.99	1	1.468460	1.50	2.1026	
24.	360	0.4	0.35	0.99	2	2.691094	2.70	0.3298	
25.	360	0.4	0.33	0.9	2	2.729921	2.79	2.1533	
26.	360	0.55	0.35	0.99	3	2.972977	3.03	1.8819	
27.	360	0.7	0.33	0.9	2	1.819311	1.85	1.6588	
28.	340	0.55	0.33	0.99	1	2.223514	2.24	0.7359	
29.	360	0.7	0.3	0.99	2	1.755022	1.734	1.2123	
30.	360	0.55	0.33	1.05	1	1.973888	2.00	1.3055	
31.	360	0.55	0.3	0.99	1	1.694913	1.66	2.1032	
32.	380	0.7	0.33	0.99	2	1.389713	1.407	1.2286	
33.	360	0.4	0.33	1.05	2	2.467231	2.47	0.1120	
34.	360	0.55	0.3	0.99	3	2.769425	2.80	1.0919	
35.	360	0.55	0.33	0.99	2	2.235817	2.201	1.5818	

36.	380	0.55	0.33	1.05	2	1.587369	1.564	1.4942
37.	340	0.7	0.33	0.99	2	2.438860	2.456	0.6978
38.	360	0.55	0.35	1.05	2	2.552994	2.56	0.2736
39.	340	0.55	0.3	0.99	2	2.805121	2.80	0.1828
40.	360	0.4	0.33	0.99	3	3.083116	3.01	2.4291
41.	360	0.55	0.33	0.99	2	2.235817	2.23	0.2608
42.	360	0.55	0.35	0.99	1	2.041213	2.00	2.0606
43.	380	0.55	0.35	0.99	2	1.820154	1.863	2.2997
44.	360	0.7	0.33	1.05	2	2.031317	1.99	2.0762
45.	360	0.55	0.33	1.05	3	2.641038	2.65	0.3381
46.	380	0.55	0.33	0.99	1	1.358366	1.35	0.6197

The predicted values and the experimental values of Surface roughness are compared with each other and graphically shown in the figure 6.

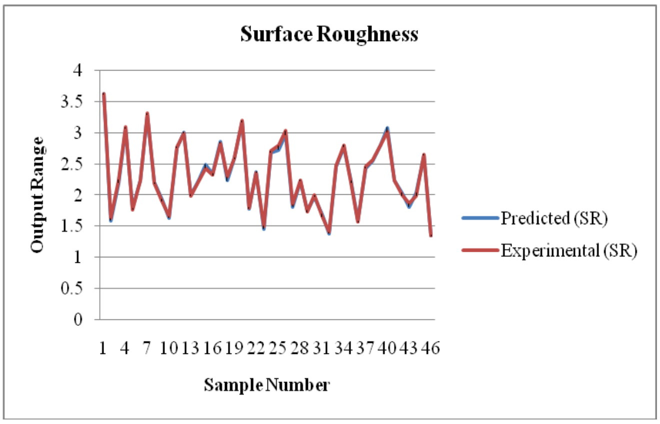

Figure 6. *Predicted Values and the Experimental Values of Surface Roughness*

7. Results and Discussion

The effects of five process parameters ie, Pressure, Abrasive flow rate, Orifice diameter, Focusing tube diameter and standoff distance and their effects on material removal rate and surface roughness is analyzed and studied using the experimental values.

a) Effects of Process Parameters on Material Removal Rate

The figure 7 shown below explains the estimated response surface for MRR regarding the water pressure (P) and abrasive flow rate (m_f) process parameters. It is shown that the MRR tends to increase as the P and m_f increases i.e, when the P is 3800 bar and m_f is 0.7 kg/min. The high pressure results in high velocity of water jet which results in the high material rate. Similarly MRR is low when the P is 3400 bar and the m_f is 0.4 kg/min. The figure 8 shows that the MRR tends to increase as the m_f increases and d_o decreases i.e, when m_f is 0.7kg/min and d_o is 0.3mm. The decreasing orifice diameter increases the velocity of water jet which results in high MRR. The figure 9 shows that the MRR tends to increase as the P increases and the s is low i.e, when P is 3800 bar and s is 1mm. Since s is low, the pressure impact on the surface is very high which results in high velocity increases the MRR. The figure 10 shows that the MRR increases as P increases and d_o at any diameter from 0.3 to 0.35mm, it gives high MRR. Finally the figure 11 shows that the MRR increases as m_f increases with decrease in d_f i.e., when m_f is 0.7 kg/min and d_f gradually decreases from 1.05mm and t0 0.9mm. Thus from the contour plots of the chosen five machining parameters on material removal rate shown below (figure 7 to figure 11), it is studied that the major influencing parameters are pressure, abrasive flow rate and standoff distance and the minor influencing parameters are orifice diameter and focusing nozzle diameter to provide maximum MRR.

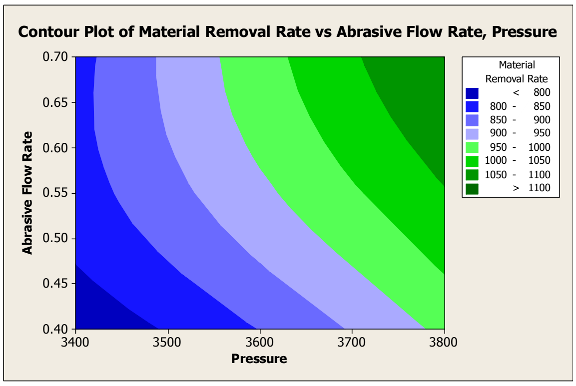

Figure 7. *Effect of Material Removal Rate Vs Pressure and Abrasive Flow Rate*

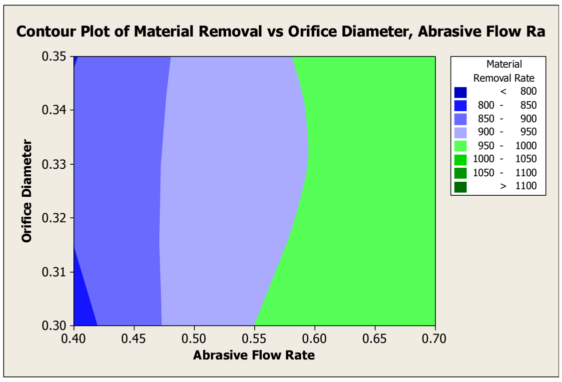

Figure 8. *Effect of Material Removal Rate Vs Abrasive Flow Rate and Orifice Diameter*

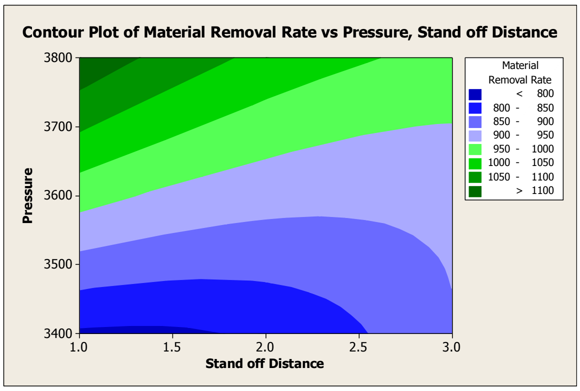

Figure 9. *Effect of Material Removal Rate Vs Stand off Distance and Pressure*

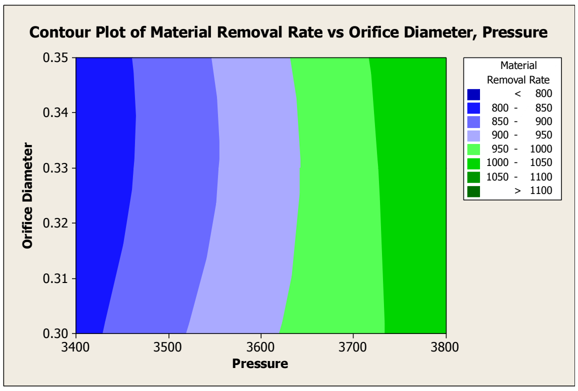

Figure 10. *Effect of Material Removal Rate Vs Pressure And Orifice Diameter*

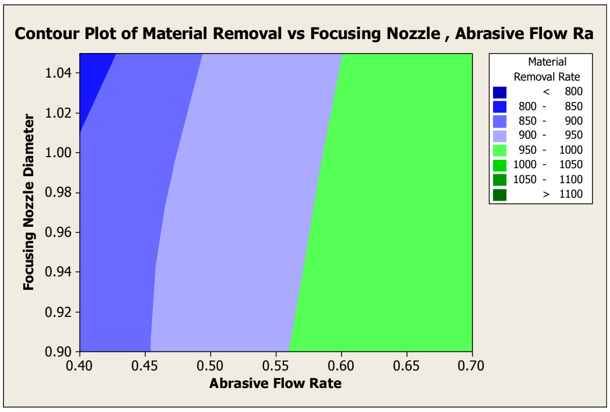

Figure 11. *Effect of Material Removal Rate Vs Abrasive Flow Rate and Focusing Tube Diameter*

b) Effects of PROCESS parameters on Surface Roughness:

Figure 12 shown below explains the estimated response surface for Surface roughness regarding pressure and abrasive flow rate. It shows as P and m_f increases, i.e., when P is 3800 bar and m_f is 0.7kg/min, the SR produced is good which is of low value. Figure 13 explains as the abrasive flow rate m_f increases and the d_0 decreases, which produces good SR, i.e., when d_0 is 0.3mm and m_f is 0.7kg/min. Figure 14 explains as d_f decreases and s decreases i.e., when d_f is 0.9mm and s is 1mm, which results the low values for SR. Figure 15 shows as the Pressure increases and standoff distance decreases obtains good SR, i.e., when P is 3800 and s is 1mm. Figure 16 illustrates as the P increases and d_o decreases results good SR, i.e, when P is 3800 bar and d_o is 0.3mm. Thus from the contour plots of the chosen five machining parameters on SR shown below (figure12 to figure 16), it is studied that the major influencing parameters are pressure, abrasive flow rate and standoff distance and the minor influencing parameters are orifice diameter and focusing nozzle diameter to provide good SR (minimum).

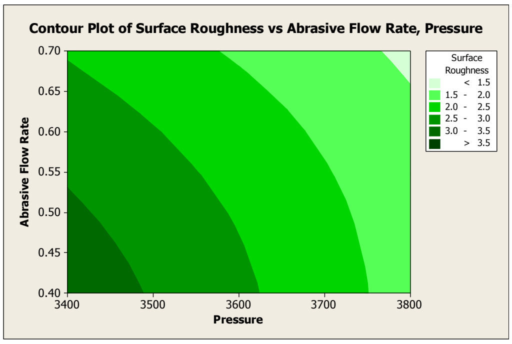

Figure 12. *Effect of Surface Roughness Vs Pressure and Abrasive Flow Rate*

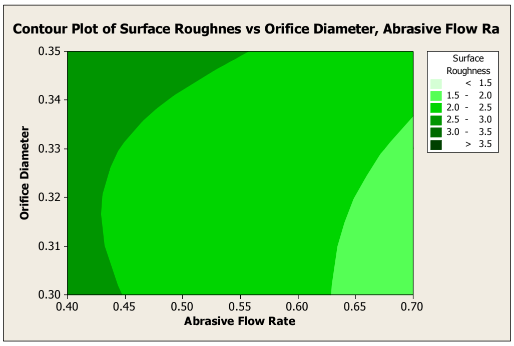

Figure 13. *Effect of Surface Roughness Vs Abrasive Flow Rate and Orifice Diameter*

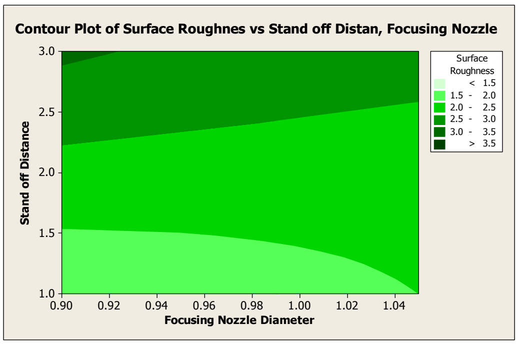

Figure 14. *Effect of Surface Roughness Vs Focusing Tube Diameter and Stand Off Distance*

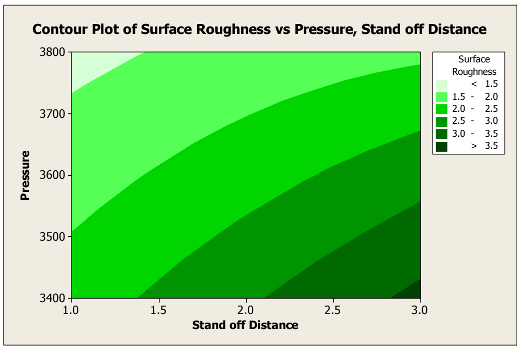

Figure 15. *Effect of Surface Roughness Vs Stand off Distance and Pressure*

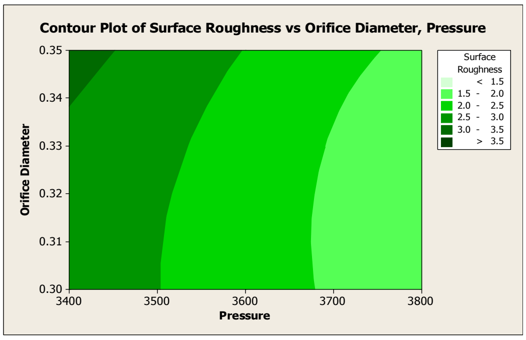

Figure 16. *Effect of Surface Roughness Vs Pressure and Orifice Diameter*

Figure 17 and 18 shows the residual plots for material removal rate and surface roughness. From the graphs the fitted values for material removal rate and surface roughness by optimization of machining parameters by abrasive waterjet maching process using Regression analysis is found to be 1035.93 mm^3/min - row 36 and 1.66 µm – row 31.

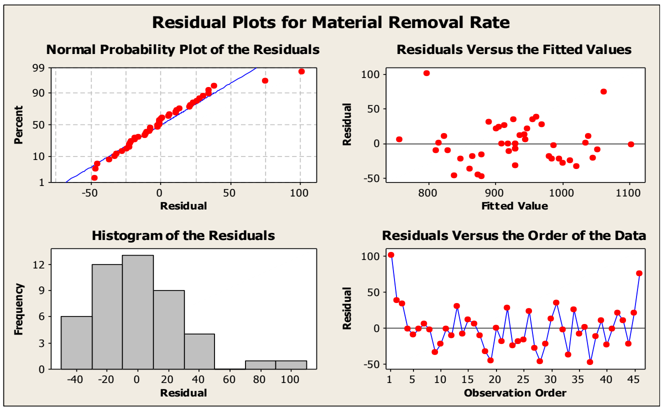

Figure 17. *Residual Plots for Material Removal Rate*

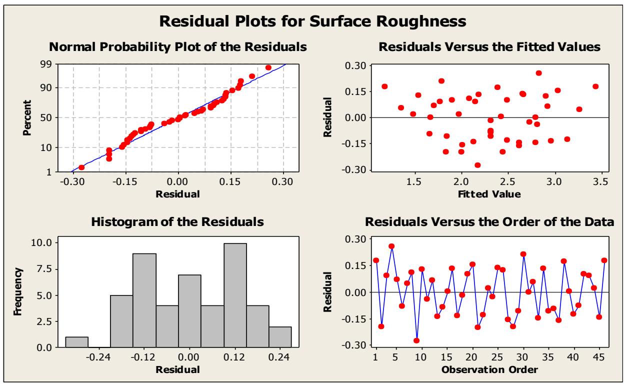

Figure 18. *Residual Plots for Surface Roughness*

8. CONCLUSION

In this paper an experimental study on material removal rate by abrasive waterjet cutting of copper iron alloy is presented. The effects of pressure, abrasive flow rate, orifice diameter, focusing nozzle diameter and standoff distance on material removal rate has been studied. From the experimental results an empirical model for the prediction of material removal rate in abrasive waterjet cutting process of copper iron alloy has been developed using regression analysis. This model was experimentally confirmed and its great consistency and applicability were within the experimental range used.

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