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Multi-Objective Optimization of Abrasive Water Jet Machining of Aluminium 6061 Alloy by Grey Relational Analysis

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ABSTRACT

Kanyakumari District, Tamilnadu State, IndiaAbstract - Last decades have witnessed a rapid growth in the development of harder, difficult and complexity to machine metals and alloys. Abrasive Water Jet Machining (AWJM) is one of the most recently developed nontraditional machining in processing different kinds of hard-to-cut materials nowadays. It is an economical method for heat sensitive materials that cannot be machined by processes that produce heat while machining. Machining parameters play the lead role in determining the machine economics and quality of machining. This paper investigates the effect and parametric optimization of five process parameters for AWJM of Aluminium 6061 alloy using Grey Relation Analysis (GRA). Based on Response Surface Methodology (RSM) different sets of experiments were conducted on this element by varying five different parameters on MRR and SR. ANOVA is performed to find out the significant parameters that affects the toughness of AWJM process. The consequence of the experiments for best possible setting proves that there is extensive development in the process. The main objective of GRA is to convert the multi response variable in to a single response grade.

KEY WORDS: Abrasive Water jet Machining, Response surface methodology, Grey Relational Analysis, Material Removal Rate, Surface Roughness.

Nomenclature:

Sl.	Factors	Symbol	Unit
1.	Water Pressure	P	Bar
2.	Abrasive Flow	m_f	Kg/min
3.	Orifice	d_o	mm
4.	Focusing Nozzle	d_f	mm
5.	Stand Off	S	mm
	Material	MRR	mm^3/min
	Surface	SR	µm

1. INTRODUCTION AND RELATED STUDIES

AWJC is the recently developed processes. This technique is suitable for machining of brittle materials like glass, ceramics and stones as well as for composite materials and ferrous and non-ferrous materials. From the literature review of Momber and Kovacevic (1992) consider this technology is less sensitive to material properties as it does not cause chatter, has no thermal effects, impose minimal stresses on the work piece, and has high machining versatility and high flexibility. Hashish (1989) reviewed that in this method, a stream of small abrasive particles is introduced in the water jet and this combination abrasive water jet is then directed to impact on the working area to cut it. A 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.

Asokan (2008), in their work, current, voltage, flow rate and gap are considered as machining parameters and MRR and SR are the objectives. Then by applying GRA, they calculated the grey grade for representing multi-objective model. Multiple regression model and ANN model have been developed to map the relationship between process parameters and objectives in terms of grade. Chakradhar (2011), in their investigation the effect and parametric optimization of process parameters for electrochemical machining of EN-31 steel using GRA. C. L. Lin in his, addresses an approach based on the Taguchi method with GRA for optimizing turning operations with multiple performance characteristics. From the literature review of Natarajan (2011), optimization of micro-EDM with multiple performance characteristics using Taguchi Method and GRA has been done. From Lin (2002), the use of the GRA based on an orthogonal array and fuzzy-based Taguchi method for optimizing the multi-response process is reported in EDM process. In this work, optimization of AWJM process of Aluminium 6061 alloy by GRA has been presented.

2. MATERIALS AND METHODS

2.1. Materials: Aluminium 6061 alloy, an American element is a precipitation hardening aluminium alloy which is available in several forms such as tube, ingot, ribbon, wire, foil, bar, pipe and rod. It is one of the cheapest American element alloy. The important factor in selecting Aluminum 6061 alloy is their high strength to weight ratio, appearance, and their non-magnetic properties. Some of the applications of Aluminium 6061 alloy include marine fittings, aerospace maintenance, transport, bicycle frames, brake components, valves couplings etc. It is also applied in paint removal, surgery, peening, drilling turning etc. It has good surface finish and can be anodized. It has excellent corrosion resistance to atmospheric conditions. Its density is 2.7g/cm^3 and its Modulus of Elasticity E = 80GPa. The dimension of this Aluminium 6061 alloy plate used for this study is 150mm x 50mm x 50mm is shown in Fig. 1.

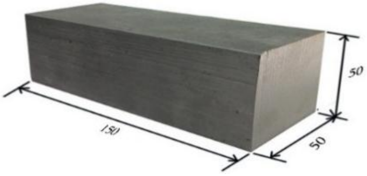


Fig.1.Aluminium 6061 alloy

2.2. Response Surface Methodology: Response Surface Methodology is a collection of mathematical and statistical techniques that are useful for modeling and analysis of problems. In the present study five process parameters are chosen and varied at three levels which were shown in Table 1 and the commonly used constant parameters of AWJM is shown in Table 2. Table 3 shows the steps involved in the RSM optimization process.

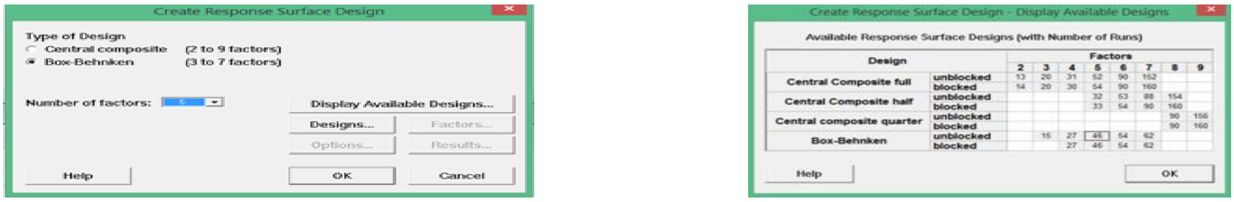
Table.1.Levels of parameters used in experiment

Levels	Water Pressure(P)Bar	Abrasive Flow Rate (m_f)Kg/m^3	Orifice Diameter(d_o)m	Focusing Nozzle Diameter(d_f)mm	Stand Off Distance (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

Parameters	Type / Value
Jet impact Angle	Neutral nozzle position (90°)
Nozzle Length	76.2 mm
Size of Abrasive material	80 mesh garnet
Type of Abrasive material	Hard rock
Diameter of Abrasive particles	0.18mm
Density of Garnet particles	4100 kg/m^3
Composition of Garnet	36% FeO, 33% SiO_2, 20% Al_2O_3, 4%MgO, 3% TiO_2, 2% CaO and 2% MnO_2

In response surface design, a Box-Behnken design table with 46 experiments was selected and were shown in Fig. 2. The parameters and levels were selected according to the review of some journals that has been recognized on AWJC on Titanium, Mild Steel, Copper, and Epoxy Composite Laminate.



Type of Design
○ Central composite (2 to 9 factors)
● Box-Behnken (3 to 7 factors)

Number of factors: 5

Available Response Surface Designs (with Number of Runs)

Design		Factors 2	3	4	5	6	7	8	9
Central Composite full	unblocked	13	20	31	52	90	152		
	blocked	14	20	30	54	90	160		
Central Composite half	unblocked				32	53	88	154	
	blocked				33	54	90	160	
Central composite quarter	unblocked							90	156
	blocked							90	160
Box-Behnken	unblocked		15	27	46	54	62		
	blocked			27	46	54	62		

Fig.2.Selection of Box-Behnken Design and Selection of No of Factors

Table.3.Steps involved in RSM optimization process

Steps	Process	Steps	Process
First	Response surface Methodology Design	Fifth	Analysis of Variance
Second	Experimental Datas of MRR and SR	Sixth	Determination of Optimal Design
Third	Mathematical Modeling for MRR and SR	Seventh	Confirmation Test
Fourth	Grey Relational Analysis		

2.2. 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 Aluminium 6061 alloy as per the Box-Behnken design considered. The machine or the equipment used to cut the American element Aluminium 6061 alloy was the AWJC machine is equipped with KMT ultrahigh pressure pump with the designed pressure of 4000bar, 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 water jet system programmed by numerical control code is used to adjust the transverse speed and control the supplement of abrasives. After the water is pumped at very high pressures resulting in high velocity of water jet of 1000 m/s as it comes out of the nozzle cuts the materials of the required size and shape. The KMT abrasive water jet cutting machine is shown in Fig.3 with its mixing chamber.

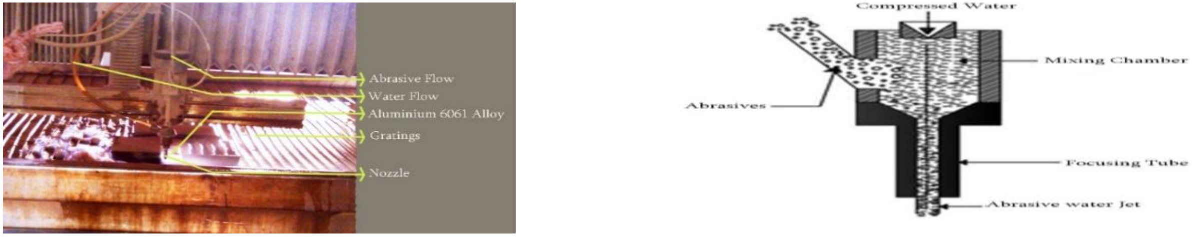


Fig.3.Experimental Setup of AWJM with Mixing Chamber

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

Pressure (Bar)	Abrasive Flow Rate (Kg/min)	Orifice Diameter (mm)	Focusing Tube Diameter (mm)	Stand Off Distance (mm)	MRR mm^3/min	SR (μm)	Pressure (Bar)	Abrasive Flow Rate (Kg/min)	Orifice Diameter (mm)	Focusing Tube Diameter (mm)	Stand Off Distance (mm)	MRR mm^3/min	SR (μm)
3400	0.55	0.33	0.99	3	48.611	3.5	3600	0.4	0.35	0.99	2	49.226	2.2
3600	0.55	0.33	0.9	1	53.639	2.0	3600	0.4	0.33	0.9	2	48.916	2.3
3600	0.55	0.3	1.05	2	51.851	2.2	3600	0.55	0.35	0.99	3	51.169	2.5
3600	0.55	0.33	0.9	3	50.835	2.5	3600	0.7	0.33	0.9	2	55.955	2.1
3800	0.55	0.33	0.9	2	62.222	1.9	3400	0.55	0.33	0.99	1	49.226	2.6
3600	0.55	0.33	0.99	2	51.851	2.1	3600	0.7	0.3	0.99	2	56.772	2.1
3400	0.4	0.33	0.99	2	45.751	3.2	3600	0.55	0.33	1.05	1	50.835	1.9
3600	0.7	0.35	0.99	2	53.639	1.8	3600	0.55	0.3	0.99	1	51.851	1.9
3800	0.55	0.33	0.99	3	61.242	2.0	3800	0.7	0.33	0.99	2	64.814	1.7
3800	0.55	0.3	0.99	2	62.222	2.0	3600	0.4	0.33	1.05	2	48.611	2.4
3600	0.55	0.33	0.99	3	51.169	2.5	3600	0.55	0.3	0.99	3	52.199	2.6
3400	0.55	0.33	1.05	2	47.716	3.0	3600	0.55	0.33	0.99	2	52.910	2.2
3600	0.4	0.33	0.99	1	50.179	1.9	3800	0.55	0.33	1.05	2	59.829	1.9
3600	0.55	0.33	0.99	2	52.910	2.1	3400	0.7	0.33	0.99	2	51.851	2.8
3600	0.55	0.35	0.9	2	54.390	2.0	3600	0.55	0.35	1.05	2	51.169	2.3
3600	0.55	0.3	0.9	2	51.851	2.7	3400	0.55	0.3	0.99	2	48.916	3.2
3400	0.55	0.33	0.9	2	48.611	3.3	3600	0.4	0.33	0.99	3	48.309	2.6
3600	0.55	0.33	0.99	2	52.910	2.1	3600	0.55	0.33	0.99	2	53.272	2.1
3600	0.4	0.3	0.99	2	47.716	2.3	3600	0.55	0.35	0.99	1	52.552	1.8
3400	0.55	0.35	0.99	2	48.309	2.9	3800	0.55	0.35	0.99	2	59.372	1.8
3800	0.4	0.33	0.99	2	58.478	1.8	3600	0.7	0.33	1.05	2	56.772	2.0
3600	0.7	0.33	0.99	3	54.773	2.2	3600	0.55	0.33	1.05	3	51.169	2.7
3600	0.7	0.33	0.99	1	56.360	1.6	3800	0.55	0.33	0.99	1	61.242	1.7

In DoE, 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 is shown in Table 4. The MRR is calculated experimentally using the following formula;

$$\text{MRR} = (\text{Initial Weight - Final Weight}) / \text{Machining Time} = (m_f – m_i) / t$$

Where, m_f = mass of the material after machining, m_i = mass of the material before machining, t = Machining Time.

The SR for the machined Aluminium 6061 alloy is measured using portable surface roughness tester.

2.3. Grey Relational Analysis: GRA is applied to find out the best selection of machining parameters for any machining process. According to the RSM design 46 sets of experiments are chosen for the experimentation and MRR and SR is found out. The higher-the-better performance for MRR may affect the performance because SR may insist lower-the-better characteristics. Hence, multi-response optimization characteristics are complex. In this part, the use of RSM with the GRA optimization methodology for multi-response optimization is discussed. The Table 5 shows the steps performed in optimization of the process using GRA.

Table.5.Steps in Optimization using Grey Relational Analysis

Steps	Process
First	Prepossessing the data results of MRR and SR.
Second	Grey relational generation is performed and Grey relational coefficient is calculated.
Third	Using the GRC values GRG is calculated by averaging the Grey relational coefficient.
Fourth	ANOVA is done to find out which parameter drastically affects the process and optimal design is identified.
Fifth	Confirmation experiment is done by setting the optimal process parameters to provide the optimal design confirmation.

The following formulas are applied to find the Normalizing the experimental results, Grey relational coefficient and Grey relational grade. For higher the better quality and lower the better quality, Normalizing the experimental results is given by,

$$X_i(k) = (y_i(k) - \min y_i(k)) / (\max y_i(k) - \min y_i(k)) \quad (1)$$

$$X_i(k) = (\max y_i(k) - y_i(k)) / (\max y_i(k) - \min y_i(k)) \quad (2)$$

Where, $X_i(k)$ is the value after grey relation generation, min $y_i(k)$ is the smallest value of $y_i(k)$ for the kth response, max $y_i(k)$ is the largest value of $y_i(k)$ for the kth response, Calculating the grey relational coefficient from the normalized values yield.

$$\gamma(x_o(k), x_i(k)) = (\Delta\min + \zeta\ \Delta\max) / (\Delta_{oj}(k) + \zeta\ \Delta\max) \quad (3)$$

Where, j=1,2...n; k=1,2...m, n is number of experimental data and m is number of responses, $X_o(k)$ is reference sequence ($x_o(k)$=1, k=1, 2...m); $x_j(k)$ is specific comparison sequence, $\Delta_{oj}=\|x_o(k)-x_j(k)\|$= The absolute value of the difference between $x_o(k)$ and $x_j(k)$, $\Delta\min = \min\min\|x_o(k)-x_j(k)\|$ is the smallest value of $x_j(k)$, $\Delta\max = \max\max\|x_o(k)-x_j(k)\|$ is the largest value of $x_j(k)$, ζ is the distinguishing coefficient in the range $0 \le \zeta \le 1$ (the value may adjusted based on the practical needs of the system).

Calculating the grey relational grade is done by averaging the grey relational coefficient which yields:

$$\gamma j = \frac{1}{k}\sum \gamma ij \quad (4)$$

γj is grey relational grade for jth experiment and k is number of performance characteristics. The normalized data results for MRR and SR is shown in Table 6, the grey relational co-efficient from normalized values for MRR and SR is shown in Table 7 and Table 8 depicts the influence of process parameters of Grey Relational Grade for Aluminium 6061 alloy.

3. RESULTS

Table.6.Normalized Data Results

Material Removal Rate	Surface Roughness	Normalized Values for MRR	Normalized Values for SR	Material Removal Rate	Surface Roughness	Normalized Values for MRR	Normalized Values for SR
48.6111	3.57	0.150001049	0	49.2264	2.29	0.182277897	0.677248677
53.6399	2.08	0.413797264	0.788359788	48.9168	2.36	0.166037182	0.64021164
51.8519	2.21	0.320003987	0.71957672	51.1696	2.50	0.284212514	0.566137566
50.8352	2.55	0.266670863	0.53968254	55.9552	2.14	0.535251165	0.756613757
62.2222	1.90	0.863999748	0.883597884	49.2264	2.65	0.182277897	0.486772487
51.8519	2.19	0.320003987	0.73015873	56.7721	2.18	0.578103361	0.735449735
45.7516	3.20	0	0.195767196	50.8352	1.90	0.266670863	0.883597884
53.6399	1.80	0.413797264	0.936507937	51.8519	1.99	0.320003987	0.835978836
61.2423	2.07	0.812597046	0.793650794	64.8148	1.70	1	0.989417989
62.2222	2.05	0.863999748	0.804232804	48.6111	2.40	0.150001049	0.619047619
51.1696	2.54	0.284212514	0.544973545	52.1999	2.68	0.338259054	0.470899471
47.7164	3.08	0.103067691	0.259259259	52.9101	2.20	0.375514079	0.724867725
50.1792	1.99	0.232259012	0.835978836	59.8291	1.99	0.738464686	0.835978836
52.9101	2.17	0.375514079	0.740740741	51.8519	2.80	0.320003987	0.407407407
54.3901	2.08	0.453150573	0.788359788	51.1696	2.34	0.284212514	0.650793651
51.8519	2.79	0.320003987	0.412698413	48.9168	3.23	0.166037182	0.17989418
48.6111	3.30	0.150001049	0.142857143	48.3092	2.69	0.134164254	0.465608466
52.9101	2.19	0.375514079	0.73015873	53.2725	2.18	0.394524529	0.735449735
47.7164	2.36	0.103067691	0.64021164	52.5526	1.80	0.35676067	0.936507937
48.3092	2.95	0.134164254	0.328042328	59.3724	1.82	0.714507533	0.925925926
58.4785	1.89	0.66761614	0.888888889	56.7721	2.03	0.578103361	0.814814815
54.7731	2.25	0.473241638	0.698412698	51.1696	2.73	0.284212514	0.444444444
56.3607	1.68	0.556522515	1	61.2423	1.72	0.812597046	0.978835979

Table.7.Grey Relational Coefficient for each Performance Co-efficient

Material Removal Rate	Surface Roughness	GRC Values for MRR	GRC Values for SR	Material Removal Rate	Surface Roughness	GRC Values for MRR	GRC Values for SR
48.6111	3.57	0.76923	1	49.2264	2.29	0.732839	0.424719
53.6399	2.08	0.547167	0.38809	48.9168	2.36	0.750709	0.438515
51.8519	2.21	0.609753	0.409978	51.1696	2.50	0.637582	0.468983
50.8352	2.55	0.65217	0.480916	55.9552	2.14	0.482975	0.397895
62.2222	1.90	0.366569	0.361377	49.2264	2.65	0.732839	0.506702
51.8519	2.19	0.609753	0.406452	56.7721	2.18	0.463777	0.404711
45.7516	3.20	1	0.718631	50.8352	1.90	0.65217	0.361377
53.6399	1.80	0.547167	0.348066	51.8519	1.99	0.609753	0.374257

61.2423	2.07	0.380924	0.386503	64.8148	1.70	0.333333	0.335702
62.2222	2.05	0.366569	0.383367	48.6111	2.40	0.76923	0.446809
51.1696	2.54	0.637582	0.478481	52.1999	2.68	0.596474	0.514986
47.7164	3.08	0.829094	0.658537	52.9101	2.20	0.571093	0.408207
50.1792	1.99	0.682818	0.374257	59.8291	1.99	0.403726	0.374257
52.9101	2.17	0.571093	0.402985	51.8519	2.80	0.609753	0.55102
54.3901	2.08	0.524576	0.38809	51.1696	2.34	0.637582	0.434483
51.8519	2.79	0.609753	0.547826	48.9168	3.23	0.750709	0.735409
48.6111	3.30	0.76923	0.777778	48.3092	2.69	0.788439	0.517808
52.9101	2.19	0.571093	0.406452	53.2725	2.18	0.558956	0.404711
47.7164	2.36	0.829094	0.438515	52.5526	1.80	0.583594	0.348066
48.3092	2.95	0.788439	0.603834	59.3724	1.82	0.41169	0.350649
58.4785	1.89	0.428223	0.36	56.7721	2.03	0.463777	0.380282
54.7731	2.25	0.513747	0.417219	51.1696	2.73	0.637582	0.529412
56.3607	1.68	0.473251	0.333333	61.2423	1.72	0.380924	0.338104

Table.8.Influence of Process Parameters of Grey Relational Grade

Material Removal Rate	Surface Roughness	Grade	Order	Material Removal Rate	Surface Roughness	Grade	Order
48.6111	3.57	0.884615	1	49.2264	2.29	0.578779	15
53.6399	2.08	0.467629	31	48.9168	2.36	0.594612	11
51.8519	2.21	0.509866	22	51.1696	2.50	0.553282	19
50.8352	2.55	0.566543	16	55.9552	2.14	0.440435	35
62.2222	1.90	0.363973	44	49.2264	2.65	0.619771	9
51.8519	2.19	0.508102	23	56.7721	2.18	0.434244	36
45.7516	3.20	0.859316	2	50.8352	1.90	0.506774	24
53.6399	1.80	0.447617	34	51.8519	1.99	0.492005	25
61.2423	2.07	0.383714	41	64.8148	1.70	0.334517	46
62.2222	2.05	0.374968	43	48.6111	2.40	0.608019	10
51.1696	2.54	0.558032	17	52.1999	2.68	0.55573	18
47.7164	3.08	0.743815	4	52.9101	2.20	0.48965	26
50.1792	1.99	0.528538	21	59.8291	1.99	0.388992	40
52.9101	2.17	0.487039	28	51.8519	2.80	0.580387	13
54.3901	2.08	0.456333	33	51.1696	2.34	0.536033	20
51.8519	2.79	0.57879	14	48.9168	3.23	0.743059	5
48.6111	3.30	0.773504	3	48.3092	2.69	0.653124	7
52.9101	2.19	0.488772	27	53.2725	2.18	0.481834	29
47.7164	2.36	0.633805	8	52.5526	1.80	0.46583	30
48.3092	2.95	0.696137	6	59.3724	1.82	0.381169	42
58.4785	1.89	0.394111	39	56.7721	2.03	0.42203	37
54.7731	2.25	0.465483	32	51.1696	2.73	0.583497	12
56.3607	1.68	0.403292	38	61.2423	1.72	0.359514	45

The comparison between the experimental grade values and predicted grade values and percentage deviation between them are depicted in Table 9.

Table.9.Percentage deviation between experimental and predicted grade

Material Removal Rate	Surface Roughness	Experimental Grade	Predicted Grade	Percentage Deviation	Material Removal Rate	Surface Roughness	Experimental Grade	Predicted Grade	Percentage Deviation
48.611	3.57	0.884615	0.79005	10.6896	49.226	2.29	0.578779	0.58085	0.359177
53.639	2.08	0.467629	0.47528	1.636376	48.916	2.36	0.594612	0.59883	0.710722
51.851	2.21	0.509866	0.54124	6.15442	51.169	2.50	0.553282	0.55762	0.785231
50.835	2.55	0.566543	0.57560	1.599845	55.955	2.14	0.440435	0.43355	1.563151
62.222	1.90	0.363973	0.37565	3.209353	49.226	2.65	0.619771	0.68972	11.28759
51.851	2.19	0.508102	0.49107	3.350973	56.772	2.18	0.434244	0.44148	1.666764
45.751	3.20	0.859316	0.81328	5.356773	50.835	1.90	0.506774	0.48243	4.803232
53.639	1.80	0.447617	0.41557	7.159206	51.851	1.99	0.492005	0.48321	1.787029
61.242	2.07	0.383714	0.42509	10.78522	64.814	1.70	0.334517	0.28304	15.38827
62.222	2.05	0.374968	0.38358	2.298046	48.611	2.40	0.608019	0.60598	0.333874
51.169	2.54	0.558032	0.55806	0.005619	52.199	2.68	0.55573	0.58353	5.003803
47.716	3.08	0.743815	0.74776	0.530312	52.910	2.20	0.48965	0.49107	0.291189
50.179	1.99	0.528538	0.54795	3.673915	59.829	1.99	0.388992	0.38280	1.590408
52.910	2.17	0.487039	0.49107	0.828874	51.851	2.80	0.580387	0.64799	11.64917
54.390	2.08	0.456333	0.50818	11.36248	51.169	2.34	0.536033	0.51533	3.861429

51.851	2.79	0.57879	0.53409	7.722255	48.916	3.23	0.743059	0.74854	0.737802
48.611	3.30	0.773504	0.74061	4.252553	48.309	2.69	0.653124	0.64828	0.741474
52.910	2.19	0.488772	0.49107	0.471318	53.272	2.18	0.481834	0.49107	1.918185
47.716	2.36	0.633805	0.60676	4.26562	52.552	1.80	0.46583	0.45730	1.830695
48.309	2.95	0.696137	0.72263	3.805781	59.372	1.82	0.381169	0.35767	6.164037
58.478	1.89	0.394111	0.44832	13.7569	56.772	2.03	0.42203	0.44070	4.424203
54.773	2.25	0.465483	0.48299	3.761947	51.169	2.73	0.583497	0.58275	0.126654
56.360	1.68	0.403292	0.38266	5.113666	61.242	1.72	0.359514	0.32477	9.663598

The mathematical model for the experimental data by cutting the aluminium 6061 alloy using abrasive water jet machine for MRR and SR is developed using linear regression analysis by MINITAB software. The developed regression equations are given below.

MRR = 63.5 + 0.0314 Pressure + 22.4 Abrasive Flow Rate - 5.2 Orifice Diameter - 5.91 Focusing Tube Diameter - 0.560 Standoff Distance

SR =15.2 - 0.00301 Pressure - 1.08 Abrasive Flow Rate - 4.61 Orifice Diameter - 0.542 Focusing Tube Diameter + 0.321 Standoff Distance

Grade = 0.5628 + 0.19898 Pressure 3400 - 0.03301 Pressure 3600 - 0.16597 Pressure 3800 + 0.08517 Abrasive Flow Rate 0.40 - 0.00505 Abrasive Flow Rate 0.55 - 0.08012 Abrasive Flow Rate 0.70 + 0.01713 Orifice Diameter 0.30 - 0.00835 Orifice Diameter 0.33 - 0.00878 Orifice Diameter 0.35 + 0.00346 Focusing Tube Diameter 0.90 - 0.01408 Focusing Tube Diameter 0.99 + 0.01062 Focusing Tube Diameter 1.05 - 0.04455 Stand Off Distance 1- 0.01122 Stand Off Distance 2 + 0.05577 Stand Off Distance 3

The Comparison between Predicted and Experimental values of MRR, SR and Grade is depicted in Figs. 5, 6 and 7.

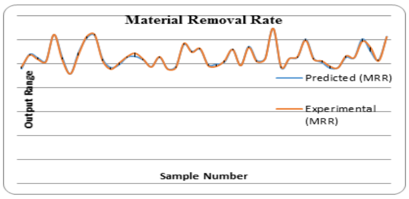


Fig.4.Comparison of Predicted MRR and Experimental MRR

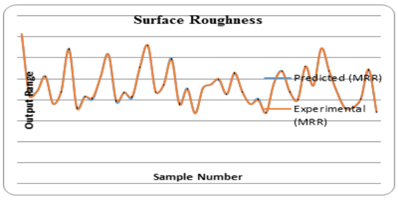


Fig.5.Comparison of Predicted SR and Experimental SR

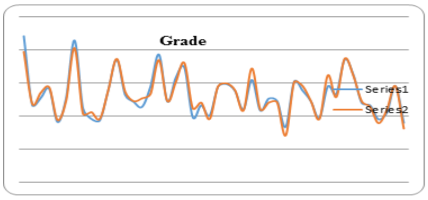


Fig.6.Comparison of Predicted Grade and Experimental Grade

3.1. Effect of Process Parameters on Grade: The contour plot shown in Fig. 7 explains the estimated response surface for Grade regarding pressure and abrasive flow rate. It shows as P and m_f decreases, i.e, when P is 3400bar and m_f is 0.4kg/min, the grade obtained is high. Fig. 8 illustrates as the standoff distance s increases and P decreases, the grade obtained is high, i.e, when s is 3mm and P is 3400bar. Fig. 9 illustrates as d_o decreases and m_f decreases i.e, when d_o is 0.3mm and m_f is 0.4kg/min the grade obtained is high. Fig. 10 shows as the standoff distance increases and abrasive flow rate decreases obtains high grade, i.e, when s is 3mm and m_f is 0.4kg/min. The residual plots for grade are depicted in Fig. 11.

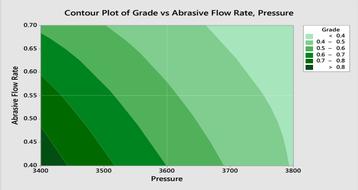


Fig.7.Grade vs Pressure and Abrasive Flow Rate

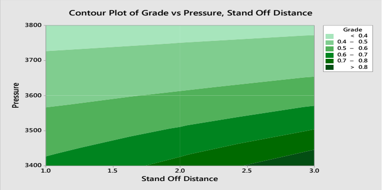


Fig.8.Grade vs Standoff distance and pressure

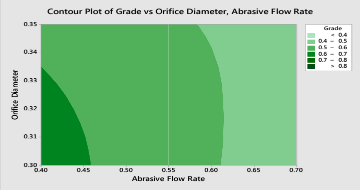


Fig. 9. Grade vs AFR and orifice diameter

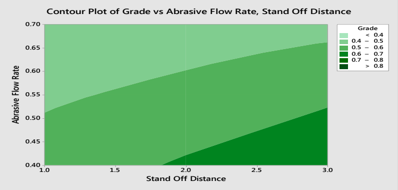


Fig.10.Grade vs Standoff distance and AFR

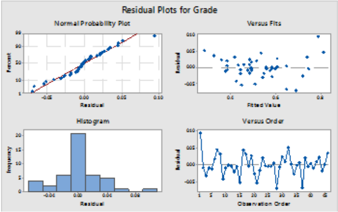


Fig.11.Residual Plots for Grade

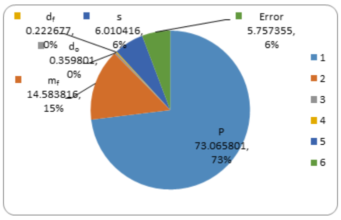


Fig.12.Contribution of Each Machining parameters in ANOVA

3.2. Analysis of Variance: ANOVA is done in Minitab software. ANOVA is a great analyzing tool to examine which design parameters extensively affect the quality feature. The conventional statistic technique acquire one parameter in a single sequence and is observed that P is the major factor for maximizing the MRR and minimizing the SR and next is the m_f, s, d_o and d_f. The increase in pressure results in high velocity of water jet that impacts on the material increases the MRR and produces good SR. The contribution of each machining parameters that affect the abrasive water jet machining process is also shown in Table 10 and Fig. 12. From the Grey relational grade plot, Interaction plot shown in Figs 13, 14 the optimal design is identified. The optimization plot for grade is shown in Fig. 15, and then the optimal design is verified by means of confirmation test.

Table.10.Analysis of Variance for Grade, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
Pressure	2	0.548296	0.553226	0.276613	224.08	0.000	73.065801
Abrasive Flow Rate	2	0.109439	0.109758	0.054879	44.46	0.000	14.583816
Orifice Diameter	2	0.002700	0.003993	0.001997	1.62	0.213	0.359801
Focusing Tube Diameter	2	0.001671	0.003926	0.001963	1.59	0.213	0.222677
Stand-Off Distance	2	0.045103	0.045103	0.022552	18.27	0.000	6.010416
Error	35	0.043204	0.043204	0.001234			5.757355
Total	45	0.750414					100
S = 0.0351342; R-Sq = 94.24%; R-Sq(adj) = 92.60%							

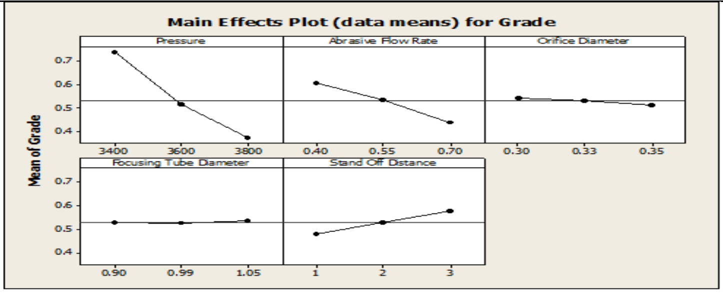


Fig.13. Grey Relational Grade Plot

3.3. Confirmation Test: Confirmation test is used to prove the accuracy of the developed model after identifying the optimal design. The experimental result which is having the high grade value using the initial arrangement of the cutting parameters is compared with the optimal one which has got from the mean effects plot shown in Fig. 15. Then the experiment is done with the new optimal design for MRR and SR and from Table 11, it is observed that the MRR increases from 48.6111mm^3/min to 51.1696 mm^3/min and SR decreases from 3.57µm to 2.71µm in the optimal combination of cutting parameters. By this test, it is understood that quality characteristics of cutting of Aluminium 6061 alloy using abrasive water jet machine could be improved to a great extent.

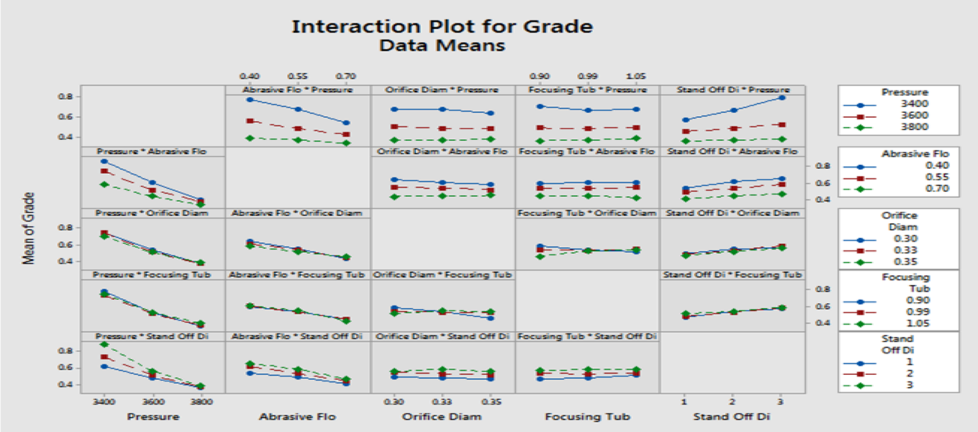


Fig.14.Interaction Plot for Grade

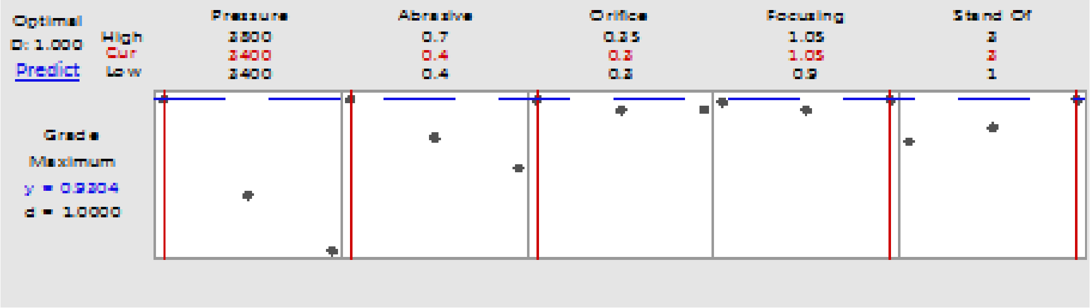


Fig.15.Optimization Plot

Table.11.Result of Confirmation Tests

Design	Process Parameters					Output Parameters	
	P (Bar)	m_f (Kg/min)	d_o (mm)	d_f (mm)	s (mm)	MRR (mm^3/min)	SR (µm)
Initial Design	3400	0.55	0.33	0.99	3	68.611	3.57
Optimal Design	3400	0.4	0.3	1.05	3	51.1696	2.51

4. CONCLUSION

In this paper, optimization of abrasive water jet machining process of Aluminium 6061 alloy by grey relational analysis has been presented. Using linear regression analysis a mathematical model is developed by Minitab software. Using ANOVA the significant parameter that affects the quality characteristics has been found out and from the main effects plot the optimal design has been identified with pressure 3400 bar, abrasive flow rate 0.4 kg/m, orifice diameter 0.3mm, focusing nozzle diameter 1.05mm and standoff distance 3mm as the best combination which provides the maximum MRR and minimum SR. By experimentation and ANOVA the optimal design is verified.

REFERENCES

Asokan P, Ravi Kumar R, Jeyapaul R, and Santhi M, Development of Multi-Objective Optimization Model for Electrochemical Machining Process, International Journal of Advanced Manufacturing Technology, 39, 2008, 55–63.

Azmira M.A, Ahsanb A.K, A Study of Abrasive Water Jet Machining Process Onglass/Epoxy Composite Laminate, Journal of Materials Processing Technology, 209, 2009, 6168–6173.

Chakradhar D and Venu Gopal A, Multi-Objective Optimization of Electrochemical Machining of EN31 Steel by Grey Relational Analysis, International Journal of Modeling and Optimization, 1 (2), 2011, 113-117.

Chithirai Pon Selvan M, and Mohanasundara Raju N, Influence of Abrasive Water Jet Cutting Conditions on Depth of Cut of Mild Steel, International journal of Design and Manufacturing Technology (IJDMT), 3 (1), 2012, 48-57.
Chithirai Pon Selvan M, and Mohanasundara Raju N, Selection of Process Parameters in Abrasive Water Jet Cutting of Copper, International Journal of Advanced Engineering Sciences and Technologies, 7 (2), 2012, 254 – 257.

Chithirai Pon Selvan M, Mohana Sundara Raju N, Modeling and Analysis of Depth of Cut in Abrasive Water Jet Cutting of Titanium, International Journal of Mechanical Engineering and Technology, 2 (2), 2011, 39-46.

Hashish M, A Model for Abrasive Water Jet Machining, Transactions of ASME Journal of Engineering Materials and Technology, III, 1989, 154-162.

Kovacevic R, Fang M, Modeling of the Influence of the Abrasive Water Jet Cutting Parameters on the Depth of Cut Based on Fuzzy Rules, International Journal of Machine Tools Manufacture, 34 (1), 1994, 55–72.

Lin C.L, Lin J.L, and Ko T.C, Optimization of the EDM Process Based on the Orthogonal Array with Fuzzy Logic and Grey Relational Analysis Method, International Journal of Advanced Manufacturing Technology, 19, 2002, 271–277.

Lin C.L, Use of the Taguchi Method and Grey Relational Analysis to Optimize Turning Operations with Multiple Performance Characteristics, Materials and Manufacturing Processes, 19 (2), 2004, 209–220.

Momber A.W, Kovacevic R, Principles of Abrasive Water Jet Machining, Springer Verlag Limited, London, 1992.

Natarajan N, and Arunachalam R.M, Optimization of Micro-EDM with Multiple Performance Characteristics Using Taguchi Method and Grey Relational Analysis, Journal of Scientific and Industrial Research, 70, 2011, 500-505.