Multi-Objective Optimization of AWJM of Lead Tin Alloy by GRA

M. Dev Anand, K.S. Jai Aultrin, G. Ramanan, R.R. Neela Rajan

Abstract--- *Last decades have witnessed a rapid growth in the development of harder, difficult and complexity to machine metals and alloys. AWJM is one of the most freshly built up non traditional machining in processing various types 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 position in bringing out the machine economics and machining quality. This research examines the persuading and parametric optimization of five parameters of the process for Abrasive water jet machining of Lead Tin alloy involving grey relation analysis. Depending upon RSM various sets of research have been performed on this element by changeable five different parameters on MRR and SR. ANOVA has been carried out to recognize the noteworthy parameters which affect toughness of abrasive waterjet machining process. The consequence of the experiments for best possible setting proves that there is extensive development in the process. The main objective of grey relational analysis is to translate the multi response variable in to a single response grade.*

Keywords--- *Abrasive Water Jet Machining, Grey Relational Analysis, Response Surface Methodology, Material Removal Rate, Surface Roughness.*

I. NOMENCLATURE

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

II. INTRODUCTION AND LITERATURE SURVEY

AWJC, a known and the recently built up method is suitable for machining of brittle materials namely stones, glass and ceramics as well as for ferrous, composite materials and non-ferrous materials.

From the literature review of Momber and Kovacevic (1992) consider this technology is not as much of responsive to properties of material since it has not created chatter, without heat effects, inflict stresses of minimum level over the workpiece, and possess greater usefulness in machining and much flexibility [1]. Hashish M. (1989) reviewed that in this technique, a rivulet of little particles that are abrasive is pioneered in the waterjet and this combination abrasive water jet is later intended to impact on the working area to cut it [2]. In AWJC, less effort was taken for modeling and optimizing the parameters for the process. The move engaged along this track comprises regression modeling, fuzzy logics, Analysis Of Variance (ANOVA), artificial neural networks and Design of Experiments (DOE). Few of these research offer increase to numerous numerical equations brought out for forecasting the output parameters [3].

R. Ravi Kumar, M. Santhi & R. Jeyapaul & P. Asokan in their paper [4], flow rate, voltage, current and gap are measured as metal removal rate, machining parameters and surface roughness were the targets. Later on application of grey relational analysis, they calculated the grey grade to represent multi-objective model. ANN model and multiple regression model were built up to plot the association among parameters of the process and targets known as grade. D. Chakradhar, A. Venu Gopal in their paper [5], examines the process parameters optimization and effect for Electrochemical machining of EN-31 steel involving grey relation analysis. C. L. Lin in his article [6], deal with a technique depending on the Taguchi method along grey relational analysis for optimizing turning operations along the multiple performance characteristics. From the literature review of R.M. Arunachalam and N. Natarajan [7], optimization of micro-EDM along numerous concert distinctiveness involving Grey Relational Analysis and Taguchi Method has been done.

From J. L. Lin, T. C. Ko and C. L. Lin paper [8], the utilize the grey relational analysis depending upon an orthogonal array and fuzzy-based Taguchi method to optimize the multi-response process is accounted in EDM process.

In this paper, optimization of abrasive water jet machining process of Lead Tin alloy by grey relational analysis has been presented.

III. EXPERIMENTAL WORK

Material

The well known American element named Lead Tin alloy, exist in numerous appearances namely tube, ribbon, ingot, foil, wire, bar, rod and pipe.

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Significant feature in choosing Lead Tin alloy is their high strength to weight ratio, their resistance against corrosion by numerous chemicals, their high thermal and electrical conductivity, reflectivity and appearance, non toxicity and their easiness of formability and machinability and non magnetic properties. Few applications of Lead Tin alloy include aerospace maintenance, brake components, bicycle frames, Marine fittings, transport, valves couplings etc. It is also applied in paint removal, surgery, peening, drilling turning etc. Good surface finish exists and could also be anodized. Exclusive corrosion resistance to atmospheric conditions exists. Density of it is 11.035g/cm3 and its Modulus of Elasticity E = 80GPa. Lead Tin alloy plate dimension utilized in this research is 150mm x 50mm x 50mm. shown in Figure 1.

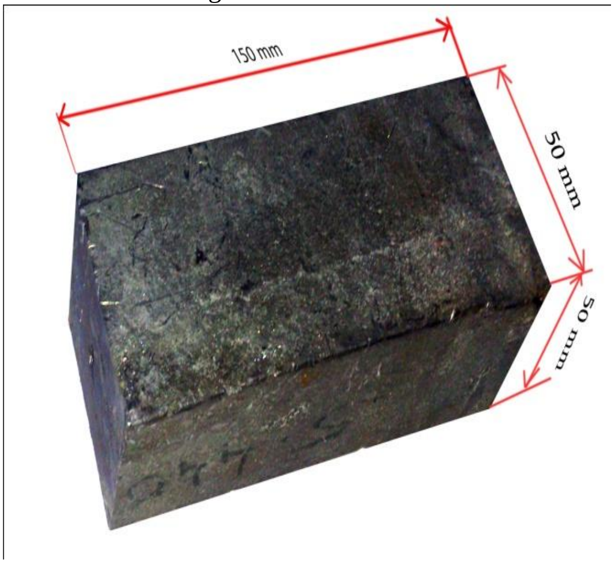


Figure 1: Lead Tin Alloy

Response Surface Methodology

Response Surface Methodology is a gathering of numerical and statistical techniques which seems to be helpful to model and analyse troubles. In the present study five process parameters are chosen and assorted at three levels that have been exhibited in Table 1 and the frequently utilized parameters that seem to be constant of AWJM is illustrated in Table 2. Table 3 depicts the steps concerned in the RSM optimization process.

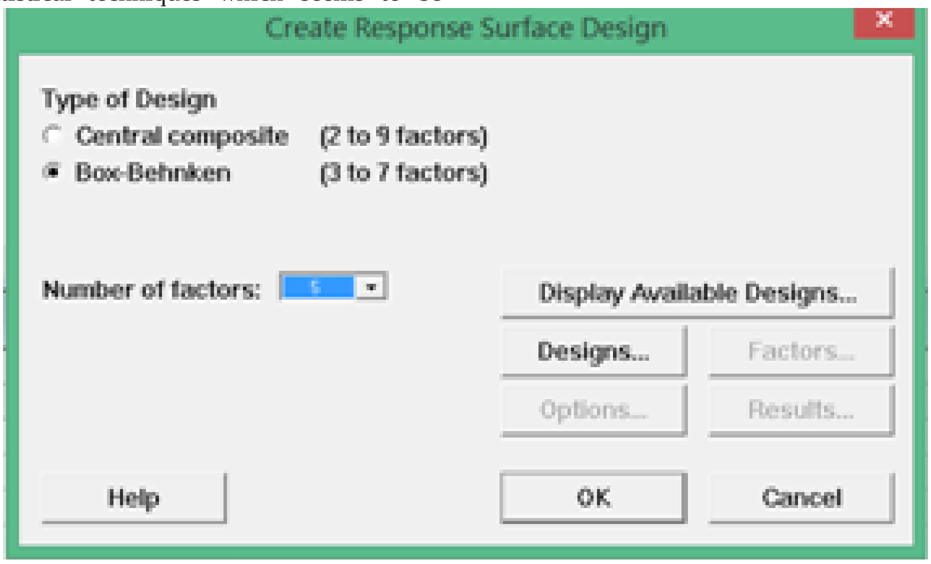
Table 1: Levels of Parameters Used in Experiment

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

Table 2: Constant Parameters

Sl.	**Parameters**	**Type / Value**
1.	Jet Impact Angle	Neutral nozzle position (90°)
2.	Nozzle Length	76.2 mm
3.	Size of Abrasive	80 mesh garnet
4.	Type of Abrasive	Hard rock
5.	Diameter of	0.18mm
6.	Density of Garnet	4100 kg/m^3
7.	Composition of garnet	36% FeO, 33% SiO_2, 20% Al_2O_3, 4%MgO, 3% TiO_2,

Involving 46 experiments from a Box-Behnken design table, in response surface design with has been chosen and has been shown in Figure 2. The parameters and levels have been chosen as per the review of few journals which was accepted on AWJC on titanium [9], Mildsteel [10] Copper [11] and epoxy composite laminate [12].



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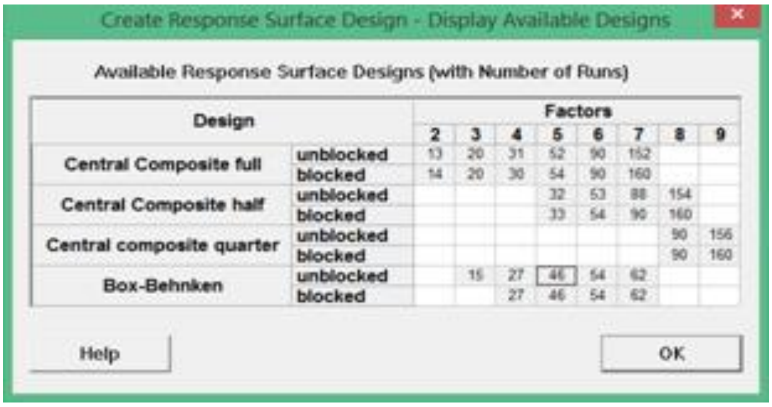


Design		Factors 2	3	4	5	6	7	8	9
Central Composite full	unblocked	13	20	31	52	90	152		
	blocked	14	20	30	54	90	160		
Central Composite half	unblocked				32	53	88	154	
	blocked				33	54	90	160	
Central composite quarter	unblocked							90	156
	blocked							90	160
Box-Behnken	unblocked		15	27	46	54	62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

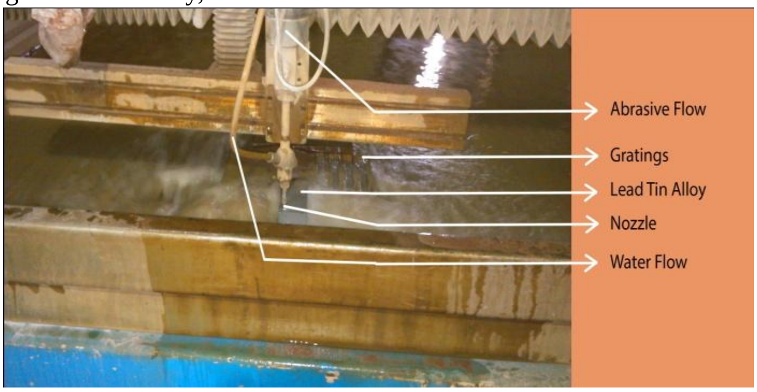
Figure 2: Selection of Box-Behnken Design and Selection of No of Factors

Table 3: Steps Involved in RSM Optimization Process

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

Data Collection and Experimentation

For all experiments the parameters involved in cutting have been accustomed to the pre-defined levels. Forty six experiment have been performed here in Lead Tin alloy according to Box-Behnken design preferred. Equipment or machine utilized for cutting Lead Tin alloy, which is the American element, was the AWJC machine has been prepared with KMT pressure pump which is ultrahigh holding the designed pressure of 4000bar, abrasive hopper which is of gravity feed type, a feeder system of abrasive, a valve controlled pneumatically and a work piece table. In the course of the controller used which is permanent in the control stand, SOD has been attuned for numerous experiments. The abrasive water jet scheme programmed using numerical control code has been utilized for adjusting the transverse speed and controlling the abrasives supplement. After the water is pumped at very high pressures resulting in greater velocity of water jet of 1000 m/s as it egress off the nozzle cuts to the desired size and shape of material. The KMT abrasive water jet cutting machine is shown in Figure 3 with its mixing chamber.



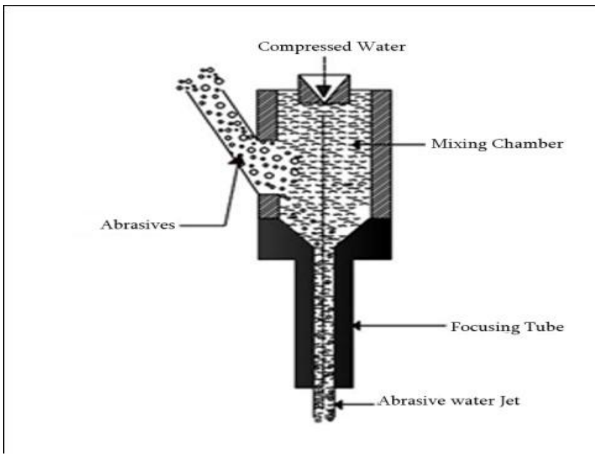


Figure 3: Experimental Setup of AWJM with Mixing Chamber

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	1709	2.45
2.	3600	0.55	0.33	0.9	1	2014.86	1.415
3.	3600	0.55	0.3	1.05	2	1970.09	1.624
4.	3600	0.55	0.33	0.9	3	1916.85	2.2
5.	3800	0.55	0.33	0.9	2	2182.26	0.788
6.	3600	0.55	0.33	0.99	2	1997.84	1.609
7.	3400	0.4	0.33	0.99	2	1688.65	2.109
8.	3600	0.7	0.35	0.99	2	1997.84	1.52
9.	3800	0.55	0.33	0.99	3	2085.98	1.201
10.	3800	0.55	0.3	0.99	2	2149.19	0.801
11.	3600	0.55	0.33	0.99	3	1896.34	2.1
12.	3400	0.55	0.33	1.05	2	1746.88	1.905
13.	3600	0.4	0.33	0.99	1	1943.11	1.887
14.	3600	0.55	0.33	0.99	2	2009.16	1.571
15.	3600	0.55	0.35	0.9	2	1948.44	1.53
16.	3600	0.55	0.3	0.9	2	2003.48	1.709
17.	3400	0.55	0.33	0.9	2	1751.19	1.9
18.	3600	0.55	0.33	0.99	2	2003.48	1.566
19.	3600	0.4	0.3	0.99	2	1842.16	1.91
20.	3400	0.55	0.35	0.99	2	1751.19	1.899
21.	3800	0.4	0.33	0.99	2	2136.25	1.211
22.	3600	0.7	0.33	0.99	3	1891.29	1.999
23.	3600	0.7	0.33	0.99	1	2055.75	1.431
24.	3600	0.4	0.35	0.99	2	1866.4	2.013
25.	3600	0.4	0.33	0.9	2	1842.16	1.945
26.	3600	0.55	0.35	0.99	3	1916.85	2.008
27.	3600	0.7	0.33	0.9	2	1970.09	1.5
28.	3400	0.55	0.33	0.99	1	1800.08	1.789
29.	3600	0.7	0.3	0.99	2	1937.8	1.699
30.	3600	0.55	0.33	1.05	1	2049.81	1.707
31.	3600	0.55	0.3	0.99	1	2009.16	1.5
32.	3800	0.7	0.33	0.99	2	2142.69	0.62
33.	3600	0.4	0.33	1.05	2	1866.4	1.934
34.	3600	0.55	0.3	0.99	3	1916.84	2.309
35.	3600	0.55	0.33	0.99	2	2014.86	1.597
36.	3800	0.55	0.33	1.05	2	2162.3	0.8
37.	3400	0.7	0.33	0.99	2	1800.08	1.9
38.	3600	0.55	0.35	1.05	2	2020.6	1.704
39.	3400	0.55	0.3	0.99	2	1768.66	2.102
40.	3600	0.4	0.33	0.99	3	1842.16	2.345
41.	3600	0.55	0.33	0.99	2	2020.6	1.64
42.	3600	0.55	0.35	0.99	1	2079.86	1.634
43.	3800	0.55	0.35	0.99	2	2162.3	0.881
44.	3600	0.7	0.33	1.05	2	1970.09	1.539
45.	3600	0.55	0.33	1.05	3	1922.04	1.997
46.	3800	0.55	0.33	0.99	1	2223.3	0.8

In Design of Experiments, depending upon Box-behnken design and Response surface methodology for five factors along 46 experiments has been chosen and performed investigational and machining time is got for every experiment is shown in Table 4. The MRR is premeditated experimentally involving the following formula;

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

Where,

m_f = material mass after machining

m_i = material mass before machining

t = Machining Time

The surface roughness for the machined Lead Tin alloy is measured utilizing Portable surface roughness tester in

National College of Engineering, Tamil Nadu, India, is shown in Figure 4.

Figure 4: Surface Roughness Tester

IV. GREY RELATIONAL ANALYSIS & RESULTS

Grey relational analysis is applied in finding out the best choice of machining parameters for any machining process.

According to the Response surface methodology design 46 sets of experiments are chosen for the experimentation and MRR and SR is found out. The higher-the-better functioning for MRR might influence the performance due to that the SR may maintain lower-the-better uniqueness. Therefore, multi-response optimization distinctiveness were known to be complex. In this part, the usage of response surface methodology with the methodology for optimization which is referred to be Grey relational analysis mainly targeting multi-response optimization has been conversed. The Table 5 shows the steps takes place in optimization of the process using Grey relational analysis.

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 premeditated.
Third	Using the GRC values GRG is calculated by averaging the Grey relational coefficient.
Fourth	ANOVA is done to determine the parameter that drastically influences the process and design which is optimal 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.

(a) For higher the better quality and lesser the better quality, Normalizing the experimental outcomes are 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 minimum value of $y_i(k)$ for the k^{th} response

$\max y_i(k)$ is the biggest value of $y_i(k)$ for the k^{th} response.

(b) Calculating the grey relational coefficient from the normalized values yield.

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

Where,

j=1,2...n; k=1,2...m, n is experimental data number and m is responses number.

$X_o(k)$ 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).

(c) Calculating the grey relational grade is done by averaging the grey relational coefficient which contributes:

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

γj is jth grey relational grade and performance numbers characteristics is k. Normalized data results for SR and MRR is depicted in Table 6, the grey relational co-efficient from normalized values for MRR and SR is illustrated in Table 7 and Table 8 depicts the authority of parameters involved in process of Grey Relational Grade for Lead Tin alloy.

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Table 6: Normalized Data Results

Sl. No.	Material Removal Rate	Surface Roughness	Normalized Values for MRR	Normalized Values for SR
1.	1709	2.45	0.038062284	0
2.	2014.86	1.415	0.610137473	0.56557377
3.	1970.09	1.624	0.526400449	0.45136612
4.	1916.85	2.2	0.426821285	0.136612022
5.	2182.26	0.788	0.923239502	0.908196721
6.	1997.84	1.609	0.578303563	0.459562842
7.	1688.65	2.109	0	0.186338798
8.	1997.84	1.52	0.578303563	0.508196721
9.	2085.98	1.201	0.743159076	0.682513661
10.	2149.19	0.801	0.861385953	0.901092896
11.	1896.34	2.1	0.38845974	0.191256831
12.	1746.88	1.905	0.108912373	0.297814208
13.	1943.11	1.887	0.475937529	0.307650273
14.	2009.16	1.571	0.599476293	0.480327869
15.	1948.44	1.53	0.485906668	0.50273224
16.	2003.48	1.709	0.58885252	0.404918033
17.	1751.19	1.9	0.116973721	0.300546448
18.	2003.48	1.566	0.58885252	0.483060109
19.	1842.16	1.91	0.287122417	0.295081967
20.	1751.19	1.899	0.116973721	0.301092896
21.	2136.25	1.211	0.837183204	0.67704918
22.	1891.29	1.999	0.379014308	0.246448087
23.	2055.75	1.431	0.686617413	0.556830601
24.	1866.4	2.013	0.332460488	0.238797814
25.	1842.16	1.945	0.287122417	0.275956284
26.	1916.85	2.008	0.426821285	0.241530055
27.	1970.09	1.5	0.526400449	0.519125683
28.	1800.08	1.789	0.208416721	0.361202186
29.	1937.8	1.699	0.466005798	0.410382514
30.	2049.81	1.707	0.675507341	0.406010929
31.	2009.16	1.5	0.599476293	0.519125683
32.	2142.69	0.62	0.849228467	1
33.	1866.4	1.934	0.332460488	0.281967213
34.	1916.84	2.309	0.426802581	0.07704918
35.	2014.86	1.597	0.610137473	0.466120219
36.	2162.3	0.8	0.885906668	0.901639344
37.	1800.08	1.9	0.208416721	0.300546448
38.	2020.6	1.704	0.620873469	0.407650273
39.	1768.66	2.102	0.149649303	0.190163934
40.	1842.16	2.345	0.287122417	0.057377049
41.	2020.6	1.64	0.620873469	0.442622951
42.	2079.86	1.634	0.731712335	0.445901639
43.	2162.3	0.881	0.885906668	0.857377049
44.	1970.09	1.539	0.526400449	0.497814208
45.	1922.04	1.997	0.43652857	0.247540984
46.	2223.3	0.8	1	0.901639344

Table 7: Grey Relational Coefficient for Each Performance Co-efficient

Sl. No.	Material Removal Rate	Surface Roughness	GRC Values for MRR	GRC Values for SR
1.	1709	2.45	0.92926045	1
2.	2014.86	1.415	0.450394669	0.469230769
3.	1970.09	1.624	0.487139304	0.525560023
4.	1916.85	2.2	0.539478331	0.785407725
5.	2182.26	0.788	0.351311216	0.355064028
6.	1997.84	1.609	0.463691318	0.521070615
7.	1688.65	2.109	1	0.728503185
8.	1997.84	1.52	0.463691318	0.495934959
9.	2085.98	1.201	0.402201142	0.422828096
10.	2149.19	0.801	0.367272777	0.356864275
11.	1896.34	2.1	0.562771702	0.723320158
12.	1746.88	1.905	0.821136214	0.626712329
13.	1943.11	1.887	0.512327875	0.619079838
14.	2009.16	1.571	0.454761966	0.510033445
15.	1948.44	1.53	0.507147397	0.498637602
16.	2003.48	1.709	0.459199011	0.552536232
17.	1751.19	1.9	0.810407288	0.624573379
18.	2003.48	1.566	0.459199011	0.508615898
19.	1842.16	1.91	0.635225207	0.628865979
20.	1751.19	1.899	0.810407288	0.62414734
21.	2136.25	1.211	0.373920341	0.424791086
22.	1891.29	1.999	0.568818955	0.669838946
23.	2055.75	1.431	0.421365804	0.47311272
24.	1866.4	2.013	0.600629107	0.676775148
25.	1842.16	1.945	0.635225207	0.644366197
26.	1916.85	2.008	0.539478331	0.674281503
27.	1970.09	1.5	0.487139304	0.490616622
28.	1800.08	1.789	0.705799263	0.580583756
29.	1937.8	1.699	0.517595237	0.549219688
30.	2049.81	1.707	0.425348258	0.551869723
31.	2009.16	1.5	0.454761966	0.490616622
32.	2142.69	0.62	0.37058216	0.333333333
33.	1866.4	1.934	0.600629107	0.639412998
34.	1916.84	2.309	0.539489218	0.866477273
35.	2014.86	1.597	0.450394669	0.517533937
36.	2162.3	0.8	0.360774655	0.356725146
37.	1800.08	1.9	0.705799263	0.624573379
38.	2020.6	1.704	0.446080681	0.550872968
39.	1768.66	2.102	0.769646019	0.724465558
40.	1842.16	2.345	0.635225207	0.897058824
41.	2020.6	1.64	0.446080681	0.530434783
42.	2079.86	1.634	0.40593894	0.528596187
43.	2162.3	0.881	0.360774655	0.368357488
44.	1970.09	1.539	0.487139304	0.50109529
45.	1922.04	1.997	0.533886542	0.668859649
46.	2223.3	0.8	0.333333333	0.356725146

Table 8: Influence of Process Parameters of Grey Relational Grade

Sl. No.	Material Removal Rate	Surface Roughness	Grade	Order
1.	1709	2.45	0.964630225	1
2.	2014.86	1.415	0.459812719	37
3.	1970.09	1.624	0.506349663	22
4.	1916.85	2.2	0.662443028	10
5.	2182.26	0.788	0.353187622	44
6.	1997.84	1.609	0.492380966	27
7.	1688.65	2.109	0.864251592	2
8.	1997.84	1.52	0.479813139	34
9.	2085.98	1.201	0.412514619	39
10.	2149.19	0.801	0.362068526	42
11.	1896.34	2.1	0.64304593	11
12.	1746.88	1.905	0.723924271	5
13.	1943.11	1.887	0.565703856	20
14.	2009.16	1.571	0.482397705	33
15.	1948.44	1.53	0.502892499	24
16.	2003.48	1.709	0.505867621	23
17.	1751.19	1.9	0.717490333	6
18.	2003.48	1.566	0.483907454	32
19.	1842.16	1.91	0.632045593	15
20.	1751.19	1.899	0.717277314	7
21.	2136.25	1.211	0.399355714	40
22.	1891.29	1.999	0.61932895	17
23.	2055.75	1.431	0.447239262	38
24.	1866.4	2.013	0.638702128	14
25.	1842.16	1.945	0.639795702	13
26.	1916.85	2.008	0.606879917	18
27.	1970.09	1.5	0.488877963	28
28.	1800.08	1.789	0.64319151	12
29.	1937.8	1.699	0.533407462	21
30.	2049.81	1.707	0.48860899	29
31.	2009.16	1.5	0.472689294	35
32.	2142.69	0.62	0.351957747	45
33.	1866.4	1.934	0.620021053	16
34.	1916.84	2.309	0.702983246	8
35.	2014.86	1.597	0.483964303	31
36.	2162.3	0.8	0.358749901	43
37.	1800.08	1.9	0.665186321	9
38.	2020.6	1.704	0.498476824	25
39.	1768.66	2.102	0.747055789	4
40.	1842.16	2.345	0.766142015	3
41.	2020.6	1.64	0.488257732	30
42.	2079.86	1.634	0.467267564	36
43.	2162.3	0.881	0.364566071	41
44.	1970.09	1.539	0.494117297	26
45.	1922.04	1.997	0.601373096	19
46.	2223.3	0.8	0.34502924	46

Assessment against the experimental grade values and forecasted grade values and percentage deviation between them are depicted in Table 9.

Table 9: Percentage Deviation between Experimental and Predicted Grade

Sl. No.	Material Removal Rate	Surface Roughness	Experimental Grade	Predicted Grade	Percentage Deviation
1.	1709	2.45	0.964630225	0.869708	9.840270667
2.	2014.86	1.415	0.459812719	0.466349	1.421509344
3.	1970.09	1.624	0.506349663	0.522838	3.256314332
4.	1916.85	2.2	0.662443028	0.647952	2.187513126
5.	2182.26	0.788	0.353187622	0.343554	2.727621603
6.	1997.84	1.609	0.492380966	0.486789	1.135699129
7.	1688.65	2.109	0.864251592	0.842123	2.560434086
8.	1997.84	1.52	0.479813139	0.485218	1.126451333
9.	2085.98	1.201	0.412514619	0.482760	17.02857977
10.	2149.19	0.801	0.362068526	0.362490	0.116407273
11.	1896.34	2.1	0.64304593	0.636974	0.944245153
12.	1746.88	1.905	0.723924271	0.725658	0.23949036
13.	1943.11	1.887	0.565703856	0.577971	2.168474513
14.	2009.16	1.571	0.482397705	0.486789	0.910305913
15.	1948.44	1.53	0.502892499	0.504358	0.291414283
16.	2003.48	1.709	0.505867621	0.527682	4.312270218
17.	1751.19	1.9	0.717490333	0.730501	1.813357764
18.	2003.48	1.566	0.483907454	0.486789	0.595474574
19.	1842.16	1.91	0.632045593	0.639304	1.148399241
20.	1751.19	1.899	0.717277314	0.726114	1.231976262
21.	2136.25	1.211	0.399355714	0.455176	13.97758546
22.	1891.29	1.999	0.61932895	0.628813	1.53134288
23.	2055.75	1.431	0.447239262	0.447209	0.006766337
24.	1866.4	2.013	0.638702128	0.615980	3.557546892
25.	1842.16	1.945	0.639795702	0.620367	3.036704067
26.	1916.85	2.008	0.606879917	0.643564	6.044702052
27.	1970.09	1.5	0.488877963	0.489606	0.148920019
28.	1800.08	1.789	0.64319151	0.688105	6.982910914
29.	1937.8	1.699	0.533407462	0.508542	4.661626273
30.	2049.81	1.707	0.48860899	0.461505	5.54717389
31.	2009.16	1.5	0.472689294	0.485285	2.664690404
32.	2142.69	0.62	0.351957747	0.324415	7.825583333
33.	1866.4	1.934	0.620021053	0.615524	0.725306449
34.	1916.84	2.309	0.702983246	0.666888	5.134581192
35.	2014.86	1.597	0.483964303	0.486789	0.583658142
36.	2162.3	0.8	0.358749901	0.338711	5.585757814
37.	1800.08	1.9	0.665186321	0.711362	6.941766153
38.	2020.6	1.704	0.498476824	0.499514	0.20806896
39.	1768.66	2.102	0.747055789	0.749438	0.318879989
40.	1842.16	2.345	0.766142015	0.759574	0.857284309
41.	2020.6	1.64	0.488257732	0.486789	0.300810744
42.	2079.86	1.634	0.467267564	0.461961	1.135658477
43.	2162.3	0.881	0.364566071	0.339166	6.967206621
44.	1970.09	1.539	0.494117297	0.484763	1.893132873
45.	1922.04	1.997	0.601373096	0.643108	6.939935394
46.	2223.3	0.8	0.34502924	0.301157	12.71551356

The mathematical model for the experimental data by cutting the Lead Tin 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.

Material Removal Rate = -1897 + 1.0089 Pressure + 307.6 Flow Rate of Abrasive + 349 Diameter of Orifice + 62 Diameter of Focusing Nozzle - 61.02 Stand Off Distance

Surface Roughness = 12.10 - 0.002798 Pressure - 1.311 Flow Rate of Abrasive 1.33 Diameter of Orifice + 0.219 Diameter of Focusing Nozzle + 0.2820 Stand Off Distance

Grade = 0.6086 + 0.20656 Pressure 3400 - 0.02617

Pressure 3600 - 0.18039 Pressure 3800 + 0.08445 Flow Rate of Abrasive 0.40 - 0.03815 Abrasive Flow Rate 0.55 - 0.04631 Flow Rate of Abrasive 0.70 + 0.01775 Orifice Diameter 0.30 - 0.01217 Orifice Diameter 0.33 - 0.00558 Orifice Diameter 0.35 + 0.00527 Focusing Nozzle Diameter 0.90 - 0.00570 Focusing Nozzle Diameter 0.99 + 0.00043 Focusing Nozzle Diameter 1.05 - 0.07101 Stand Off Distance 1 - 0.03959 Stand Off Distance 2 + 0.11060 Stand Off Distance 3

Assessment against forecasted and experimental values of MRR, SR and Grade is depicted in Figure 5, 6 and 7.

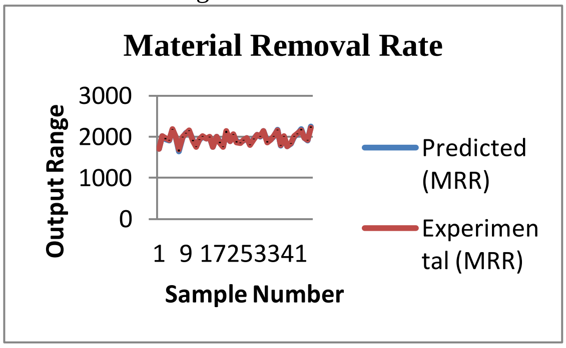

Figure 5: Comparison of Predicted &Experimental MRR

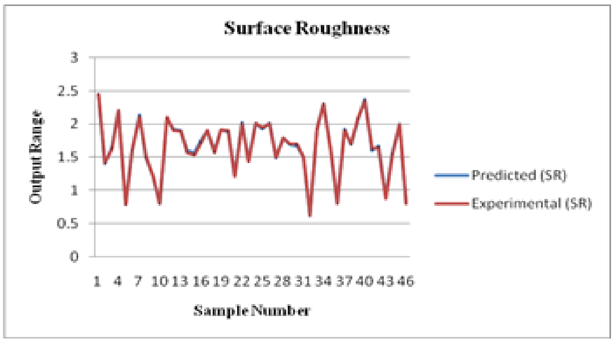

Figure 6: Comparison of Predicted & Experimental SR

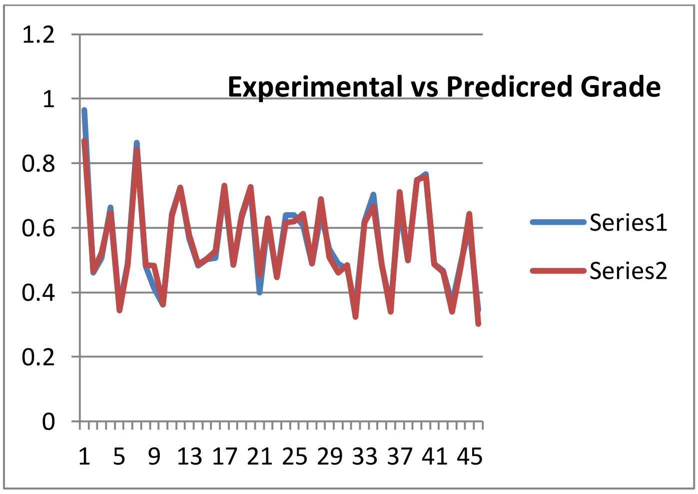

Figure 7: Comparison of Predicted Grade and Experimental Grade

Effect of Process Parameters on Grade

The contour plot showed in figure 8 briefs the anticipated response surface for Grade concerning not only pressure but also the flow rate of the abrasive. It exhibits as P and m_f decreases, i.e, once P is 3400 bar and m_f is 0.4kg/min, the grade obtained is high. Figure 9 illustrates as the stand off distance s increases and P decreases, the grade obtained is high, i.e, if s is 3mm and P is 3400 bar. Figure 10 illustrates as d_o declines and m_f declines too i.e, once d_o is 0.3mm and m_f is 0.4kg/min the grade obtained is high. Figure 11 shows as the standoff distance increases and flow rate of abrasive decreases obtains high grade, i.e, once s is 3mm and m_f is 0.4kg/min. The residual plots for grade is depicted in Figure 12.

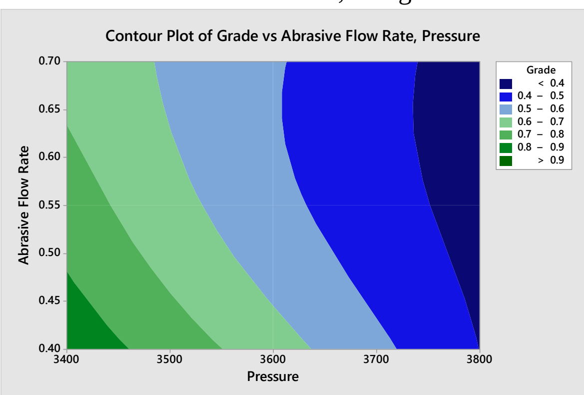

Figure 8: Grade vs Pressure and Abrasive Flow Rate

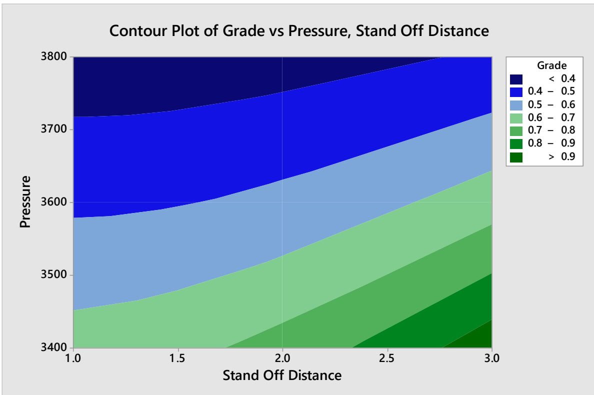

Figure 9: Grade vs Stand off Distance and Pressure

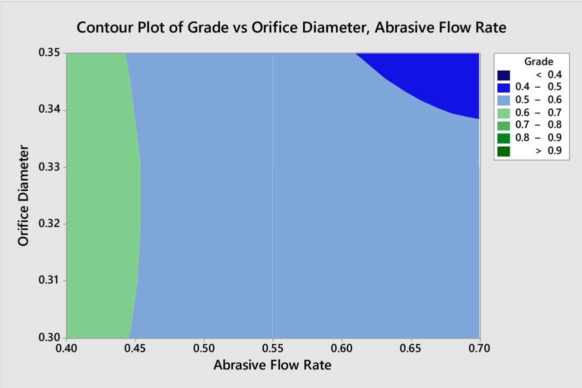

Figure 10: Grade vs AFR and Orifice Diameter

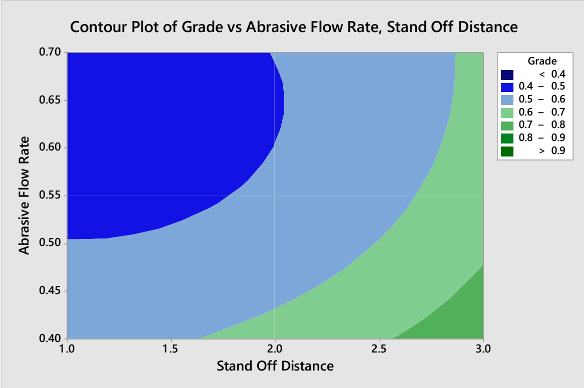

Figure 11: Grade vs Stand Off Distance and AFR

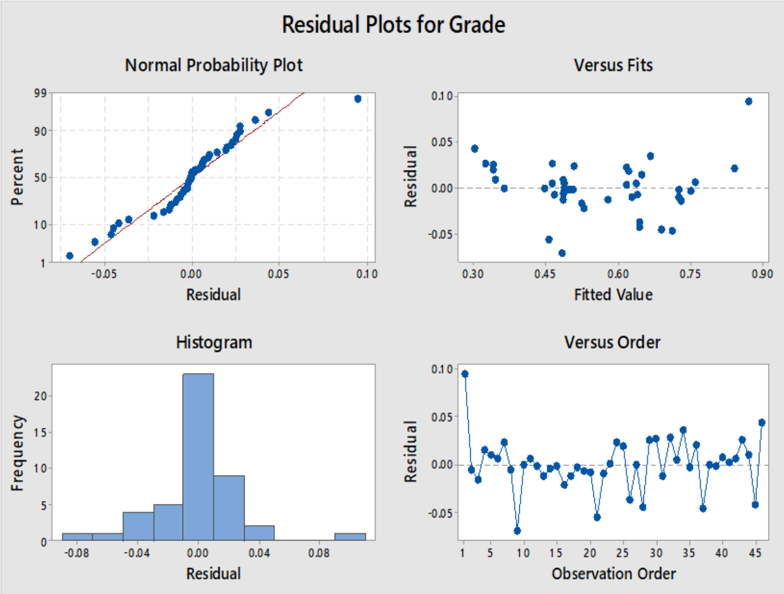

Figure 12: Residual Plots for Grade for Lead Tin Alloy

Analysis of Variance

ANOVA is done in Minitab software. ANOVA is a great analyzing tool to examine that design parameters extensively influence the quality feature. Conventional statistic method acquire single parameter in a single sequence and is noticed that P is the major factor for making the most of the MRR and least of the SR and next is the m_f, s, d_o and d_f. The increase in pressure end up in greater 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 figure 13. From the Grey relational grade plot in figure 14 the optimal design is identified and this 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	0.611775	0.611775	0.305887	313.17	0.000	67.6300
Abrasive Flow Rate	2	0.095715	0.095715	0.047857	49.00	0.000	10.7374
Orifice Diameter	2	0.004956	0.004956	0.002478	2.54	0.094	0.5559
Focusing Tube Diameter	2	0.000705	0.000705	0.000352	0.36	0.700	0.0790
Stand-off Distance	2	0.169885	0.169885	0.084943	86.97	0.000	18.0580
Error	35	0.034186	0.034186	0.000977			3.8350
Lack of Fit	31	0.034119	0.034119	0.001101	65.56	0.000	
Pure Error	4	0.000067	0.000067	0.000017			
Total	45	0.891410	0.891410				100
S = 0.0312529 R-Sq = 96.16% R-Sq(adj) = 95.07% R-sq(pred) = 93.32%							

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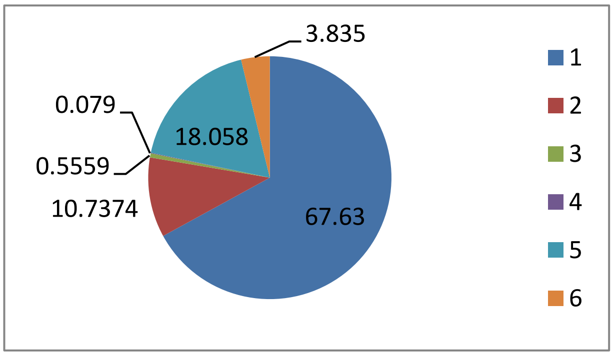

Figure 13: Contribution of Each Machining Parameters

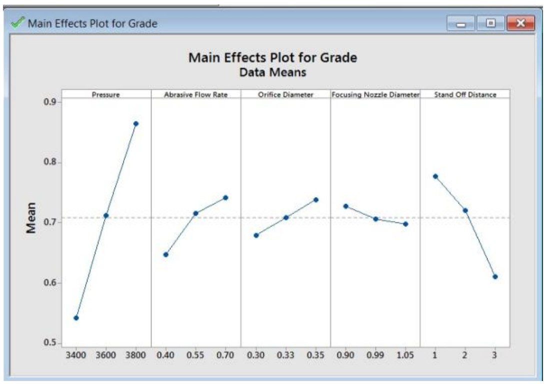

Figure 14: Grey Relational Grade Plot for Lead Tin Alloy in ANOVA

Confirmation Test

Confirmation test is utilized for proving the accurateness of the built up model after identifying the optimal design. The investigational result which is having the high grade value utilizing the preliminary arrangement of the parameters involved in cutting is assessed against the optimal one which has got from the mean effects plot shown in figure 10. 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 2142.69mm^3/min to 2144.34 mm^3/min and SR decreases from 0.620µm to 0.618µm in the optimal combination of cutting parameters. By this test, it is understood that quality characteristics of cutting of Lead Tin alloy using abrasive water jet machine could be improved to a great extent.

Table 11: Result of Confirmation Tests

Desig n	Process Parameters					Output	
	P (Ba	m_f (Kg/m	d_o (m	d_f (m	S (m	MRR (mm^3/	SR (µ
Initia	380	0.7	0.3	0.9	2	2142.69	0.6
Opti	380	0.7	0.3	0.9	1	2144.34	0.6

V. CONCLUSION

In this paper, optimization of abrasive water jet machining process of Lead Tin 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 3800bar, flow rate of abrasive 0.7kg/min, diameter of orifice 0.35mm, diameter of focusing nozzle is of 0.9mm and 1mm of standoff distance as the best combination which provides the maximum MRR and minimum SR. By experimentation and ANOVA the optimal design is verified.

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