MULTI-RESPONSE PARAMETRIC OPTIMIZATION OF ABRASIVE WATER JET MACHINING ON INCONEL-601 BY USING GREY RELATIONAL ANALYSIS

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Abstract: Use of optimization techniques for unconventional machining process has been considered as the one of the most important factor for the present manufacturing sectors. In the present scenario, industries utilizing the optimization technique to satisfy the best quality characteristic for manufacturing the good quality of products. In the present investigation the optimization process was employed to know the best suitable set of process parameters for the Abrasive water jet machining (AWJM) on Inconel-601 super alloy. Grey Relational Analysis (GRA) was adopted to determine the suitable optimal Material Removal Rate (MRR), Surface Roughness (R_a) and Kerf Width (k) for the impact of Abrasive water jet machining (AWJM) on distinct Inconel-601 super alloy. At first the material is machined on AWJM. Process parameters especially used are transverse speed, stand-off distance and abrasive flow rate on Inconel-601. To accomplish the experimental work the face cantered central composite design (CCD) of Response surface methodology (RSM) was utilized. Optimal setting process parameters were noticed by using grey relational analysis (GRA) and confirmation experiment was performed. A number of trail runs were conducted on Inconel-601 to recognize the improvement in Material removal rate (MRR), surface roughness (R_a) and kerf width (k).

Keywords: AWJM, CCD, RSM, GRA, MRR, R_a, k, INCONEL-601.

I. INTRODUCTION

In the present days, unconventional machining process has huge demand in machining the incomprehensible to fabricate and complicated profiles can be performed efficiently. Abrasive water jet machining (AWJM) is one of the most extensively used non-traditional machining process. AWJM had achieved a vital role in unconventional machining process, generally pre-claimed in the aviation, atomic and automotive industries. Thus AWJM is the best solution for the machining incomprehensible materials (such as Titanium, Nimonics and Inconel etc.,) with complicated profiles, which isn't possible by any standard machining process. In AWJM, high-speed well-concentrated water jet is used to cut the metal. To erode metal at the contact surface it uses the kinetic energy of water particle. The jet speed is sort of 600 m/s. It doesn't generate any environmental hazards. Abrasive particles are used in the water jet to cut hard materials. These abrasive particles helps to erode metal from the contact surface.

In this investigation, Inconel-601 was preferred for AWJM machining process because of its extensive Mechanical characteristics. Inconel-601 is used in several applications which requires the high strength and corrosion resistance. Inconel is a family of austenite nickel-chromium-based super alloys. In extreme conditions where the heat and pressure is subjected in such situations Inconel alloys are used.

This present study deals with the AWJM machining process of Inconel-601 with multi response optimization. Face centred Central composite design (CCD) method is used to conduct the experimental work. For multi response optimization, to find out the best results for optimal process parameters of Inconel-601 super alloy the grey relational analysis (GRA) method is used. To achieve the improvement of higher Material removal rate (MRR), lower surface roughness (Ra) and kerf width (k) the confirmation test was conducted.

II. MATERIAL AND METHOD USED

2.1 Work material

For this present investigation Inconel-601 super alloy was selected as the work material for multi response optimization of AWJM machining process parameters. The chemical composition of Inconel 601 was shown in table 1.

Table 1 chemical composition of Inconel 601

%	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Al %
COMP	0.0330	0.1600	0.3000	0.0020	0.0020	22.6500	0.1200	60.3000	1.2300
REQD	-- 0.1000	-- 0.5000	-- 1.0000	-- --	-- 0.0150	21.0000 25.0000	-- --	58.0000 63.0000	1.0000 1.7000

%	Cn	Cu	Nh %	Ti %	V %	W %	Pb%	Fe %	N%
COMP	0.1200	0.0210	0.0070	0.2100	0.0450	0.0410	--	14.7000	--
REQD	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --	-- --

Fig.2.1. Inconel 601 during AWJM machining

2.2 Illustrative of machining

The Abrasive Jet Machining method involves the applying of a high-speed stream of abrasive particles assisted by the pressurized air onto the surface through a nozzle of little diameter. Material removal takes place by abrading action of abrasive particles. Abrasive water jet machining is an erosion process technique in which water below high pressure and speed exactly cuts through and grinds away minuscule amounts of material. The addition of an abrasive substance greatly will increase the power to cut through more durable materials like steel, Inconel and titanium.

Fig.2.2. Water Jet Germany S3015 AWJM, Chennai

2.3 Experimental Design and process parameters

In this study, process parameters such as transverse speed, stand-off distance and abrasive flow rate was considered as input process parameters, which is shown in table 2. To determine the optimum settings for the AWJM process of each factor is investigated at three levels. Selection of levels and parameters was taken with the help of review of literature, importance and their compatibility as per the few investigations.

Table 2 Control factors and their levels

Symbol	Control Factors	Units	Level 1	Level 2	Level 3
A	Transverse Speed (TS)	mm/min	140	160	180
B	Stand-off Distance (SOD)	mm	6	9	12
C	Abrasive Flow Rate (AFR)	gm/min	310	320	330

Based on face centred central composite design (CCD) of response surface methodology the fourteen experimental runs with the allocated levels of process parameters were selected are shown in table 3.

Table 3 Face centered Central composite design (CCD) and Experimental results

R.no	Inputs			Outputs		
	Transverse Speed (mm/min)	Stand-off Distance (mm)	Abrasive Flow Rate (gm/min)	Material Removal Rate (gm/min)	Surface Roughness (µm)	Kerf Width (mm)
1	160	9	320	1.7466	4.3831	0.675
2	180	6	310	1.6732	5.2341	0.575
3	160	9	320	1.8233	5.1351	0.637
4	180	12	310	1.9069	5.2028	0.676
5	160	9	320	1.6838	4.7593	0.619
6	160	9	320	1.8889	4.9930	0.661
7	140	12	330	2.1180	4.3470	0.908
8	180	6	330	2.1458	4.2118	0.708
9	140	6	310	1.9780	4.4323	0.787
10	140	12	310	2.1653	4.5183	0.864
11	180	12	330	2.0020	5.3356	0.744
12	140	6	330	1.8018	5.0039	0.9
13	160	9	320	2.2417	4.4129	0.787
14	160	9	320	2.2087	4.6993	0.725

In this case the important output responses such as Material removal rate (MRR), surface roughness (Ra) and kerf width (k) were chosen for optimizing process parameters of AWJM. Mitutoyo Surf test SJ 201P surface roughness tester is used to measure the surface roughness (R_a). The kerf width of the machined surface was measured by using Video measuring system (VMS). The Material removal rate (MRR) can be calculated as

$$MRR = k\,L\,T\,\rho\,/T_m$$

Here, k is the kerf width (mm), L is the length of cut (mm), T is the thickness of work piece (mm), ρ- Density (g/cm3) and T_m is the machining time (min).

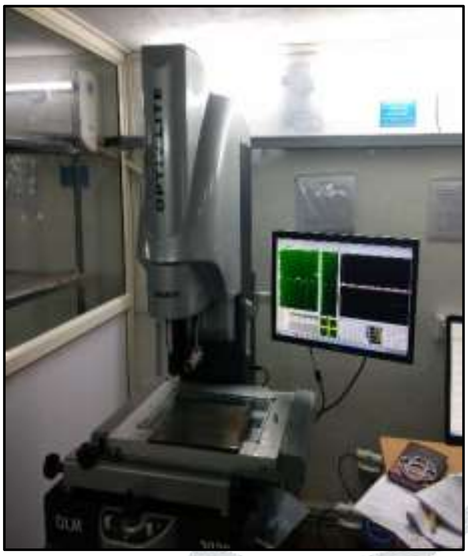

Fig 3. Video measuring system (VMS)

Fig 4. Mitutoyo Surf test SJ 201P

III. OPTIMIZATION OF AWJM PARAMERTERS USING GREY RELATIONAL ANALYSIS (GRA)

Step 1: In this step, at first initial response values are converted into the s/n ratio values. These s/n values are carried out for the further analysis. For Material removal rate (MRR) the higher-the-better performance characteristics is applicable and it can be expressed as

$$\text{S/N ratio} = -10\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}} \quad \text{(higher-the-better)} \qquad (1)$$

Where, n = number of replications, y_{ij} = observed response value, i = 1, 2....n and j = 1, 2...k. For surface roughness and kerf width the lower-the-better performance characteristics is applicable and it can be expressed as

$$\text{S/N ratio} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_{ij}^{2}\right) \quad \text{(lower-the-better)} \qquad (2)$$

The experimental results of s/n ratio values were calculated was submitted in the table 4.

Table 4 S/N ratio values

Exp. No	Output responses			S/N ratio values		
	Material removal rate (gm/min)	Kerf width (mm)	Surface roughness (µm)	Material Removal rate (Db)	Kerf width (Db)	Surface roughness (Db)
1	1.7466	0.675	4.3831	4.8438	3.4139	-12.8357
2	1.6732	0.575	5.2341	4.4709	4.8066	-14.3769
3	1.8233	0.637	5.1351	5.2173	3.9172	-14.2110
4	1.9069	0.676	5.2028	5.6066	3.4011	-14.3247
5	1.6838	0.619	4.7593	4.5256	4.1662	-13.5508
6	1.8889	0.661	4.9930	5.5243	3.5960	-13.9672
7	2.1180	0.908	4.3470	6.5184	0.8383	-12.7638
8	2.1458	0.708	4.2118	6.6316	2.9993	-12.4893

9	1.9780	0.787	4.4323	5.9243	2.0805	-12.9325
10	2.1653	0.864	4.5183	6.7102	1.2697	-13.0995
11	2.0020	0.744	5.3356	6.0293	2.5685	-14.5437
12	1.8018	0.9	5.0039	5.1142	0.9151	-13.9861
13	2.2417	0.787	4.4129	7.0115	2.0805	-12.8944
14	2.2087	0.725	4.6993	6.8829	2.7932	-13.4406

Step 2: Normalizing, the pre-processing of the data is first performed for convenient to normalize the raw data for analysis. Normalization is the process of transforming the single data input to acceptable range of data which is distributed uniformly in a scale for further analysis. In this case, a linear normalization is performed in between the range of zero and unity. The normalized Material removal rate (MRR) is the higher-the-better performance characteristics is appropriate and it can be expressed as

$$z_{ij} = \frac{y_{ij} - \min(y_{ij}, i = 1,2,...n)}{\max(y_{ij}, i = 1,2,...n) - \min(y_{ij}, i = 1,2,...n)} \quad \text{(higher-the-better)} \qquad (3)$$

For surface roughness and kerf width lower-the-better performance characteristics is appropriate and it can be expressed as

$$z_{ij} = \frac{\max(y_{ij}, i = 1,2,...n) - y_{ij}}{\max(y_{ij}, i = 1,2,...n) - \min(y_{ij}, i = 1,2,...n)} \quad \text{(lower-the-better)} \qquad (4)$$

The values of normalized responses are shown in the table 5.

Table 5 Normalized S/N values

Exp. No	S/N ratio values			Normalized S/N ratio		
	Material removal rate (gm/min)	Kerf width (mm)	Surface roughness (µm)	Material Removal rate (gm/min)	Kerf width (mm)	Surface roughness (µm)
1	4.8438	3.4139	-12.8357	0.1468	0.3510	0.1686
2	4.4709	4.8066	-14.3769	0.0000	0.0000	0.9188
3	5.2173	3.9172	-14.2110	0.2938	0.2241	0.8381
4	5.6066	3.4011	-14.3247	0.4470	0.3542	0.8934
5	4.5256	4.1662	-13.5508	0.0215	0.1614	0.5167
6	5.5243	3.5960	-13.9672	0.4146	0.3051	0.7194
7	6.5184	0.8383	-12.7638	0.8059	1.0000	0.1336
8	6.6316	2.9993	-12.4893	0.8505	0.4554	0.0000
9	5.9243	2.0805	-12.9325	0.5721	0.6870	0.2157
10	6.7102	1.2697	-13.0995	0.8814	0.8913	0.2970
11	6.0293	2.5685	-14.5437	0.6134	0.5640	1.0000
12	5.1142	0.9151	-13.9861	0.2532	0.9806	0.7286
13	7.0115	2.0805	-12.8944	1.0000	0.6870	0.1972
14	6.8829	2.7932	-13.4406	0.9494	0.5074	0.4631

Step 3: Grey Relational Coefficient, the relationship between the ideal (best) and actual normalized experimental results can be expressed. Before that, deviation sequence is performed for the reference and comparability sequence can be found out. Deviation Sequence can be expressed as follows

$$\Delta_{0,i}(k) = \left| y_0(k) - y_i(k) \right| \quad (5)$$

Where, y_0 (k) is the reference sequence and y_i (k) is the specific comparability sequence.
Grey Relational Coefficient can be expressed as follows

$$\xi_{0,i}(k) = \frac{\Delta\min + \zeta\Delta\max}{\Delta_{0,i}(k) + \zeta\Delta\max} \quad (6)$$

Where, $\Delta_{0,i}$ (k) is the deviation sequence. ζ is known as the distinguishing or identified coefficient, range is defined as $0 \le \zeta \le 1$. The ζ value is the smaller and the distinguished ability is larger. $\zeta = 0.5$ is generally used.

Table 6 Values Of Deviation Sequence and Grey Relational Coefficient.

Exp. No	Deviation Sequence			Grey Relational Coefficient		
	Material Removal Rate (gm/min)	Kerf Width (mm)	Surface Roughness (µm)	Material Removal Rate (gm/min)	Kerf Width (mm)	Surface Roughness (µm)
1	0.8532	0.6490	0.8314	0.3695	0.4351	0.3756
2	1	1	0.0812	0.3333	0.3333	0.8603
3	0.7062	0.7759	0.1619	0.4145	0.3919	0.7554
4	0.553	0.6458	0.1066	0.4748	0.4364	0.8242
5	0.9785	0.8386	0.4833	0.3382	0.3735	0.5085
6	0.5854	0.6949	0.2806	0.4607	0.4184	0.6405
7	0.1941	0	0.8664	0.7204	1	0.3659
8	0.1495	0.5446	1	0.7698	0.4787	0.3333
9	0.4279	0.313	0.7843	0.5388	0.615	0.3893
10	0.1186	0.1087	0.703	0.8083	0.8214	0.4156
11	0.3866	0.436	0	0.564	0.5342	1
12	0.7468	0.0194	0.2714	0.401	0.9627	0.6482
13	0	0.313	0.8028	1	0.615	0.3838
14	0.0506	0.4926	0.5369	0.9081	0.5037	0.4822

Step 4: Grey relational grade, by averaging the grey relational coefficient corresponding to each individual performance characteristics is defined as grey relational grade. The multiple response process of its overall performance characteristic is mainly depends on the obtained grey relational grade. Table 7 shows the grey relational grade values. The grey relational grade can be expressed as

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad (7)$$

Where, γ_i - grey relational grade for the j[th] experiment and k - number of performance characteristics.

Table 7 Grey Relational Grade Values

Exp . No	Control Factors			Grey Relational Coefficient			Grey Relational Grade	Rank
	A Transverse speed (mm/min)	B Standoff distance (mm)	C Abrasive flow rate (gm/min)	Material Removal Rate (gm/min)	Kerf Width (mm)	Surface Roughness (µm)		
1	2	2	2	0.3695	0.4351	0.3756	0.3933	14
2	3	1	1	0.3333	0.3333	0.8603	0.5089	11
3	2	2	2	0.4145	0.3919	0.7554	0.5205	9
4	3	3	1	0.4748	0.4364	0.8242	0.5784	7
5	2	2	2	0.3382	0.3735	0.5085	0.4067	13
6	2	2	2	0.4607	0.4184	0.6405	0.5065	12
7	1	3	3	0.7204	1	0.3659	0.6954	2
8	3	1	3	0.7698	0.4787	0.3333	0.5272	8
9	1	1	1	0.5388	0.615	0.3893	0.5143	10
10	1	3	1	0.8083	0.8214	0.4156	0.6817	3
11*	**3**	**3**	**3**	**0.564**	**0.5342**	**1**	**0.6993**	**1**
12	1	1	3	0.401	0.9627	0.6482	0.6706	4
13	2	2	2	1	0.615	0.3838	0.6662	5
14	2	2	2	0.9081	0.5037	0.4822	0.6313	6

Step 5: Determination of the optimal and its level combination, Fig.3.1 shows the graph for the grey relational grade which is the mean of each individual grey relational coefficient performance characteristic. The higher grey relational grade value represents the better performance characteristic. The maximum MRR, minimum R_a and k of grey relational grades are plotted in fig.3.1. The pre-owned experimental design which is face centred central composite design (CCD) helps to notice the independent effect of each machining parameter on the grey relational grade at different levels.

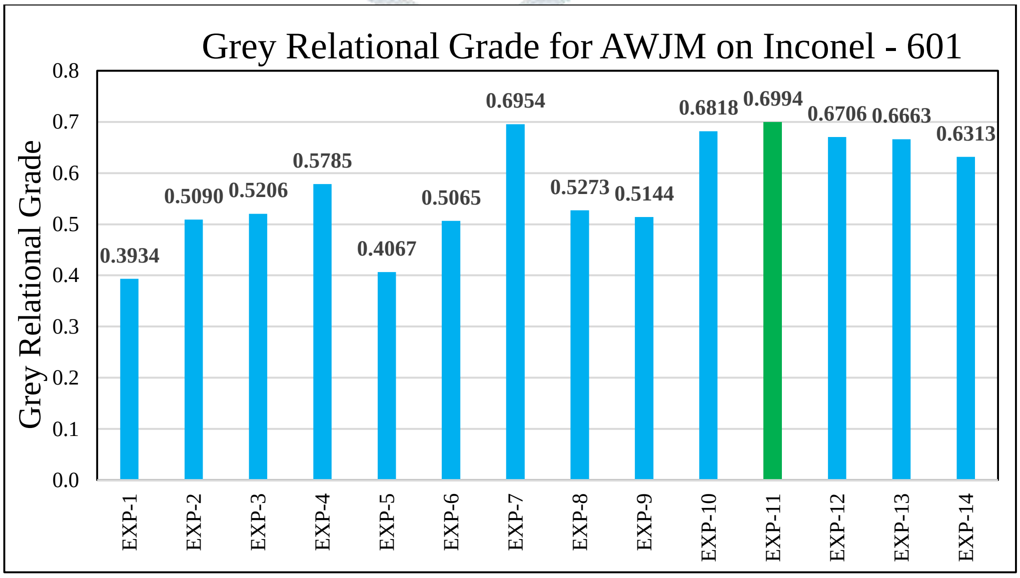

Fig 5. Grey Relational Grade Graph

For suppose, the mean of grey relational grade for the transverse speed (A) at level 1 can be calculated by averaging the grey relational grade for the experiments 7,9 to 10 and 12 respectively. Table 8 shows the mean of grey relational grade at each level of machining parameters. The higher mean of grey relational grade of each machining parameter to their corresponding levels are considered as the optimum levels. From the table 8 and fig.3.2 the combination of optimal parameter was considered as A1 (transverse speed, 140 mm/min), B3 (standoff distance, 12 mm), C3 (abrasive flow rate, 330 gm/min).

Table 8 Main effects of the factors on grey relational grade

Run	Parameters	Level 1	Level 2	Level 3	Max-Min	Rank
A	Transverse speed	**0.6406***	0.5208	0.5785	0.1198	3
B	Stand-off distance	0.5553	0.5208	**0.6638***	0.1430	**1***
C	Abrasive Flow Rate	0.5709	0.5208	**0.6482***	0.1274	2

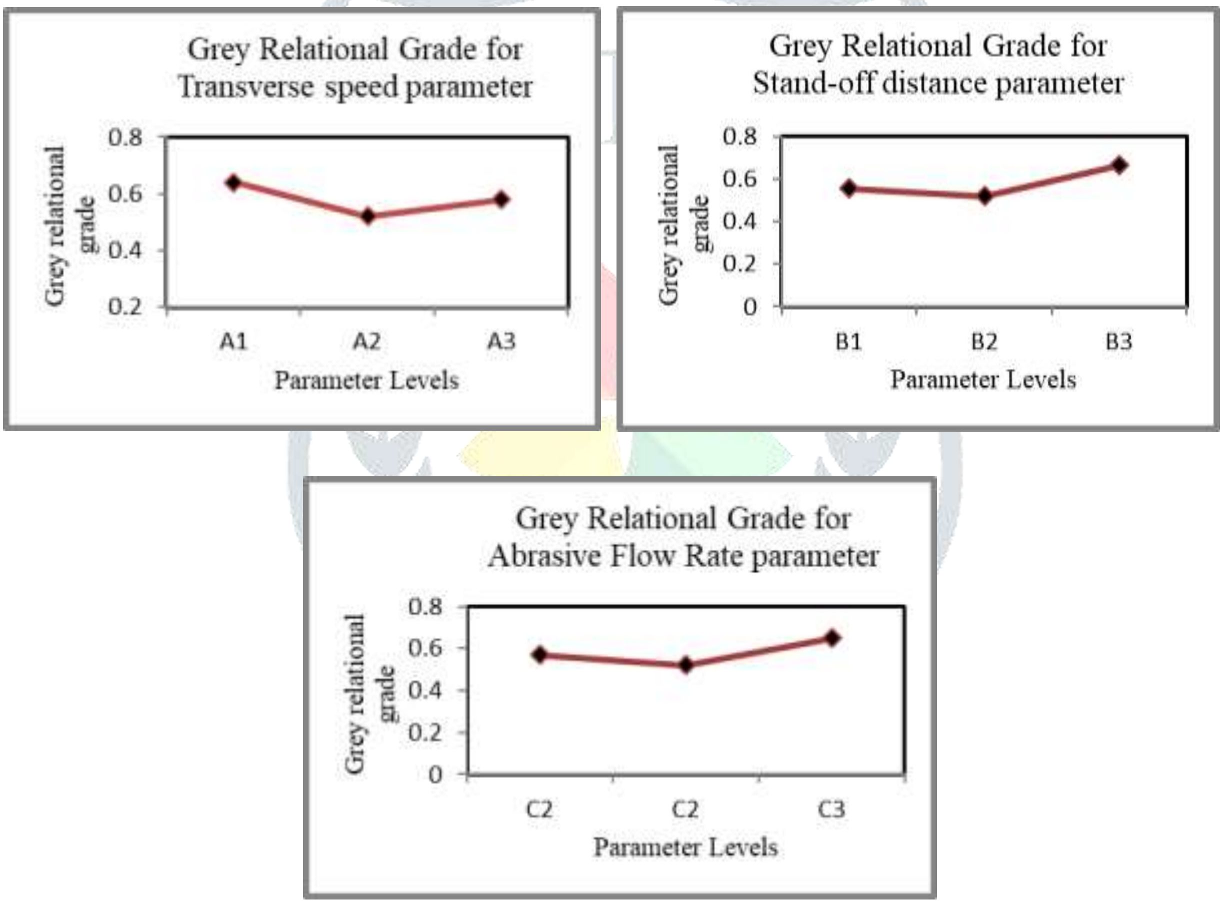

Fig 6. Grey relational grade graph for individual parameter

IV. CONFIRMATION EXPERIMENT

The confirmation test was conducted for the optimal process parameters with its selected levels to determine the quality characteristic of AWJM for Inconel 601 super alloy. From table 7 highest grey relational grade is obtained at the experiment 11 which shows the optimal process parameter set of A3B3C3 has the finest multiple performance characteristics considering the fourteen experiments. For validation purpose initial parameters A3B3C3 was compared with the confirmation results.

Table 9 Results of confirmation experiment

Level	Optimal process parameters		% of Improvement
	GRA	CONFIRAMATION EXPERIMENT	
	A3B3C3	A1B3C3	
Material Removal Rate (gm/min)	2.0020	2.0169	7.69%
Kerf Width (mm)	0.744	0.6892	7.36%
Surface Roughness (µm)	5.3356	5.0125	6.05%

From table 9, the initial process parameters A3B3C3 was compared with the optimal process parameters A1B3C3 of AWJM on Inconel-601 super alloy. Using confirmation experimental results the obtained response values are Material removal rate (MRR) = 2.0169 gm/min, kerf width (k) = 0.6892 mm and surface roughness (Ra) = 5.0125µm. The confirmation experiment results clearly shows that the increased in Material removal rate value from 2.0020 gm/min to 2.0169 gm/min, reduced the value of kerf width from 0.744 mm to 0.6892 mm and also surface roughness from 5.3356 µm to 5.0125µm respectively. The identical improvement in Material removal rate (MRR), Kerf width (k) and surface roughness (Ra) were 7.69%, 7.63% and 6.05%.

V. CONCLUSIONS

In this study, the multiple response characteristic of material removal rate (MRR), surface roughness (Ra) and kerf width (k) on Inconel-601 super alloy during Abrasive Water Jet Machining (AWJM) were optimized by using Grey relational analysis (GRA). The complicated multi response optimization can be done successfully, thus it can improve the quality performance characteristic to obtain best results in any modern manufacturing industries

i. The optimal process parameters such as 140 mm/min transverse speed, 12 mm stand-off distance and 330 gm/min abrasive flow rate which are acquired by using Grey relational analysis method for Inconel-601.
ii. The multiple response characteristic which are Material removal rate (MRR), Kerf width (k) and surface roughness (Ra) were shows the improvement of 7.69%, 7.36% and 6.05%. The Grey relational analysis method is most appropriate and comfortable process for the parametric optimization of Abrasive Water Jet Machining process.
iii. Multiple response parametric optimization of grey relational analysis method shows the finest results for machining which are the positive indications for the efficiency in the machining process.

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