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Process parameter optimization of abrasive water jet machining on monel k400 alloy

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Abstract: Nowadays it's difficult to use a metal with high corrosion resistant properties in required applications. Monel 400 is one nickel based alloy having required property to be applicable in such scenarios. It is used in highly corrosive environments such as marine, chemical and aerospace industries as it has the property of maintaining its toughness over a range of temperature, however machining of this Monel alloy is relatively tough due to its characteristic work hardening properties. To tackle the mentioned issues, Abrasive water jet machining is used which is a widely known nontraditional machining technique. The process parameters and the response variables were chosen depending on the machine specifications, and parameter combinations were made using Minitab statistical software. The parameters and their interactions like the cut quality on the alloy, nozzle diameters effects, and water pressure were also studied. Response surface model and various statistical algorithms such as S-N ratio, ANOVA and regression equations were utilized for formation of the design of experiment, optimization of process parameters for the machining process were done using Grey relations. Reduction of surface roughness, maximization of Material removal rate while simultaneously reducing the cycle time for the operation was the primary objective. The results thus obtained indicates that the quality of cut was the most influential factor in the machining process followed by water-jet pressure value.

1. Introduction

Abrasive water-jet machining is a blasting machining process which uses abrasives driven by a high velocity water-jet to wear away material from the work piece. Common applications include cutting heat-sensitive, brittle, thin, or hard materials. Precisely it is used to cut intricate shapes or form specific edge shapes. Material is removed by fine abrasive particles, usually about 0.001 in (0.025 mm) in diameter driven by a high velocity water jet stream. Pressures of the water jet ranges from 25000 to 60000 psi. AWJM machines are usually self-contained cantilever or gantry type machines. First the water pressure is increased and then is mixed with the abrasive in a mixing chamber which then exits through a convergent nozzle. Nozzles must be highly resistant to abrasion and thus are typically made of tungsten carbide or synthetic sapphire.

The varying effects of water pressure, Abrasive flow rate, Orifice diameter, focusing nozzle diameter, Stand-off distance on Material removal rate & surface roughness for Copper Iron alloy [1]. Characterization of AWJ process on the production of pockets in Inconel 718 established relations between critical process parameters which concluded that with increase in mass flow rate of abrasive the depth of cut value increased [2]. The effects of process parameter in Abrasive water jet machining were investigated using Response Surface Methodology which observed that pressure and transverse rate has much effect on surface roughness than standoff distance [3]. Based on research papers, experience, Minitab software readings & available AWJ machine specifications, input & output parameters were chosen & machining was performed on Monel k400.

2. Materials and methods

All the samples of Monel K400 alloy has a composition of 64.27% Nickel, 32.337% Copper, 0.0269% Carbon, 0.748% Manganese, 0.19% Silicon and less than 0.0017% Sulphur. The alloy has a density of 8.8 x 10^3 Kg/m^3, modulus of elasticity of 179 Gpa, Tensile strength of 550 MPa and hardness number 42 HRC.

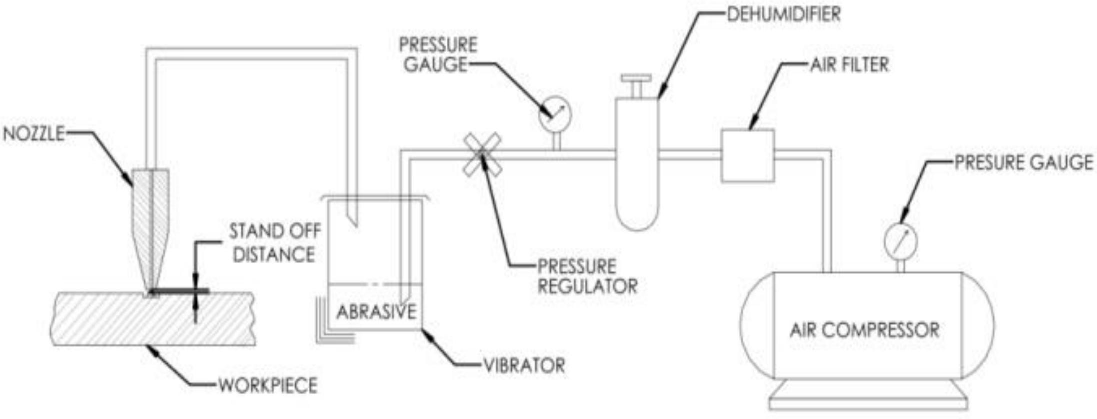

Figure 1. Setup of abrasive water jet machining.

Figure 2. Machined work piece.

The Monel K400 work piece of dimensions 410*250*5 is mounted using an Abrasive Water Jet Machine (OMAX MAXIEM 1515) that uses the garnet almanide as an abrasive (60-200 mesh), 31 holes with 10mm diameter and 31 square slots with 20mm side length are cut into the work piece. Each slot and hole is machined by varying the input parameters of the AWJM set-up. The primary objective is to increase the efficiency of the process of AWJM, this includes achieving highest material removal rate, least surface roughness of the cut, achieving optimal stand-off distance, better surface finish with lower process time and achieving minimum circularity value. SURFCOM is used to measure the surface roughness of the machined entity with high accuracy upto 0.31nm. For testing the circularity of the machined slots, Machine Vision setup (Optiv Lite OLM 3020) is used.

Design of Experiments methodology is used to determine the relationship between the input and output (cause and effect relationship) of the process. Controllable and uncontrollable input factors and responses are used in our experiment. Controllable input factors include Pressure, Stand-off distance, Quality of cut, Nozzle diameter, those of uncontrolled include unpredictable parameters such as the ambient temperature and the responses or output measures include material removal rate, surface roughness and circularity. The selection of the appropriate model for the experiments is highly imperative as it will be a deciding factor for the number of test cases that would be produced. The central composite approach was chosen as it shown to have fewer number of test cases as compared to the Box-Behnken model. For our parameter and response values we got 31 as our test case number from the central composite model. The range of the input parameters was decided and the values were entered in to the software dialog box, from wherein the software converts this given range into the test grouped combinations in a specific sequence, according to which the machining process was carried out. Response Surface Methodology is used to explore the relationships between several explanatory variables & one or more response variables. The main idea of this method is to use sequence of designed experiments to obtain an optimal response.

3. Results and observations

3.1 Output response variables.

The measurement and calculations of circularity, material removal rate and surface roughness values for the varying ranges of pressure, stand-off distance, quality of cut, nozzle diameter are tabulated in the table 1 and Main effects plot for circularity and MRR is explained in figure 3 and 4 .

Table 1. Response variable table.

MO	SR	PRESSURE	SOD	ND	QOC	SURF RGHNS	MRR	CIRCULARITY
1	11	40000	7	16	1	2.4435	18.21053	0.089
2	23	37500	4	14	5	1.7005	5.864407	0.083
3	27	40000	7	14	4	2.2424	8.238095	0.074
4	10	36000	7	16	4	1.9515	8.238095	0.087
5	5	40000	7	12	4	1.9803	7.061224	0.088
6	24	37500	4	14	2	2.2247	11.16129	0.081
7	12	40000	1	16	4	1.8523	9.611111	0.086
8	13	40000	7	16	4	2.0256	9.611111	0.068
9	25	37500	10	14	5	3.2442	11.16129	0.094
10	6	45000	10	12	5	1.8458	6.92	0.083
11	14	40000	7	16	4	2.6458	9.611111	0.075
12	15	40000	7	16	4	3.3709	9.611111	0.065
13	16	40000	7	16	4	3.245	9.611111	0.062
14	1	37500	4	12	5	1.7791	4.271605	0.09
15	17	40000	7	16	5	1.8853	7.521739	0.061
16	22	45000	7	16	4	2.1058	11.53333	0.054
17	18	40000	7	16	4	1.9211	9.611111	0.055
18	2	37500	4	12	2	1.9099	9.351351	0.08
19	3	37500	10	12	2	1.6089	9.351351	0.118
20	19	40000	7	16	4	2.0301	9.611111	0.09
21	7	45000	4	12	5	2.4861	6.92	0.11
22	28	45000	4	14	2	3.5475	15.04348	0.087
23	8	45000	10	12	2	2.8702	6.92	0.083

24	29	45000	10	14	2	2.8669	15.04348	0.095
25	4	37500	10	12	5	1.8121	4.805556	0.093
26	26	37500	10	14	2	2.1945	5.864407	0.08
27	20	40000	10	16	4	2.3431	9.611111	0.092
28	30	45000	4	14	5	1.9047	7.863636	0.07
29	31	45000	10	14	5	2.6346	7.863636	0.102
30	9	45000	4	12	2	2.2714	13.30769	0.092
31	21	40000	7	16	4	1.3913	9.611111	0.1

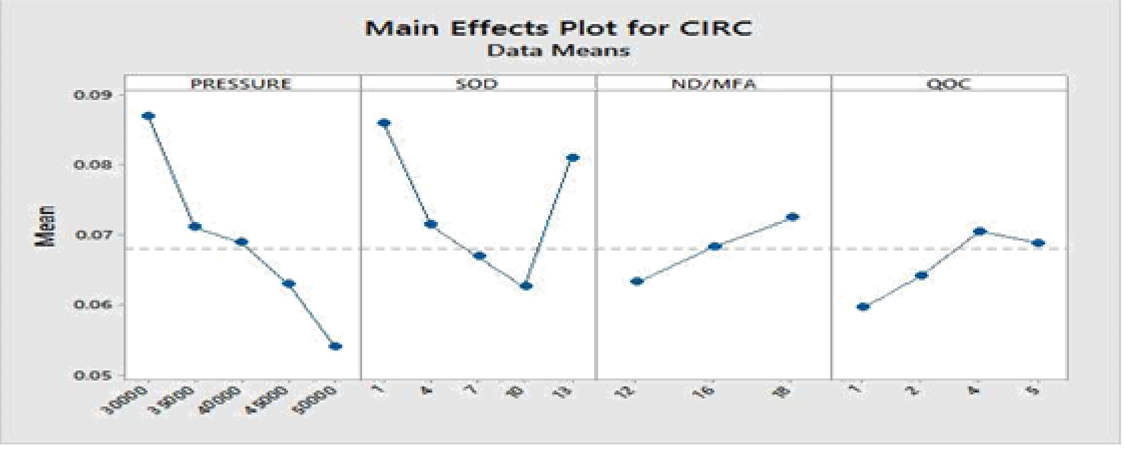

Figure 3. Main effects plot for circularity.

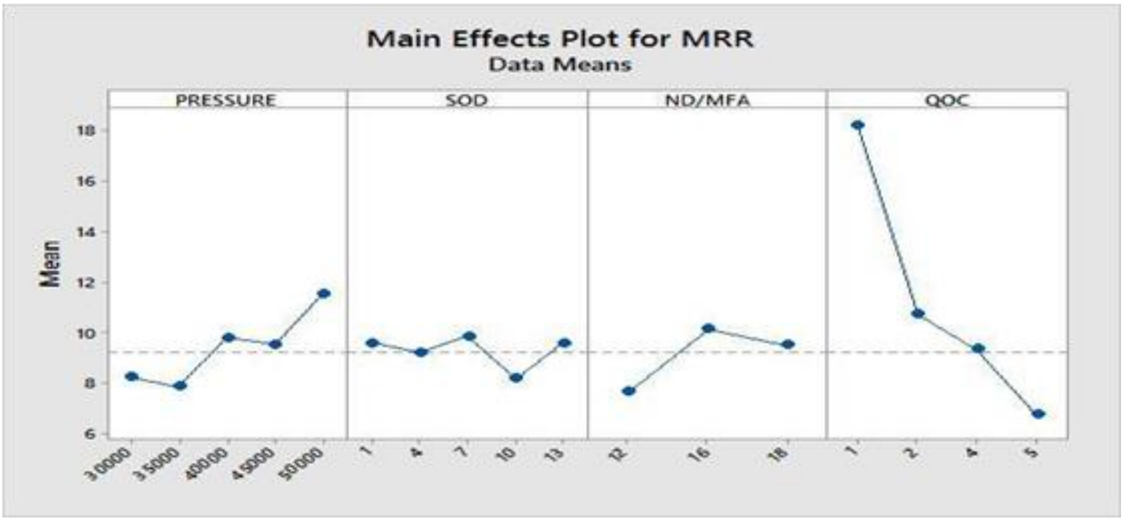

Figure 4. Main effects plot for material removal rate.

3.2 Signal to noise ratio values.

The signal-to-noise ratio measures how the response signal varies with respect to the target value under varying noise conditions. One can choose from different signal-to-noise ratios, depending on the goal of our experiment. In our experiment we have used the goal of maximizing the response of MRR, as more is the MRR value, the machining process will be much faster, and as a result the cycle time will be less. At the same time we have the goal of minimizing the response of Surface Roughness and Circularity values, so as to obtain a smoother finish and distinct, defined machined surface. The following table consists of the tabulations of the obtained S/N ratios for each our response variables. These S/N ratio are used to calculate the normalized S/N ratio's and also used to formulate the Grey coefficient and the Grey grade as in table 2

Table 2. S/N Ratio for Response Variables.

MO	SR	P	S	N	Q	S/N SR	S/N MRR	S/N CIRC
1	11	40000	7	16	1	-7.76025	25.20645	21.0122
2	23	37500	4	14	5	-4.61153	15.36448	21.61844
3	27	40000	7	14	4	-7.01426	18.31654	22.61537
4	10	36000	7	16	4	-5.80737	18.31654	21.20961
5	5	40000	7	12	4	-5.93462	16.9776	21.11035
6	24	37500	4	14	2	-6.94543	20.95429	21.8303
7	12	40000	1	16	4	-5.35423	19.65547	21.31003
8	13	40000	7	16	4	-6.13107	19.65547	23.34982
9	25	37500	10	14	5	-10.2222	20.95429	20.53744
10	6	45000	10	12	5	-5.32369	16.80212	21.61844
11	14	40000	7	16	4	-8.45114	19.65547	22.49877
12	15	40000	7	16	4	-10.5549	19.65547	23.74173
13	16	40000	7	16	4	-10.2243	19.65547	24.15217
14	1	37500	4	12	5	-5.00401	12.61182	20.91515
15	17	40000	7	16	5	-5.50761	17.52637	24.2934
16	22	45000	7	16	4	-6.46834	21.2391	25.35212
17	18	40000	7	16	4	-5.671	19.65547	25.19275
18	2	37500	4	12	2	-5.62021	19.41749	21.9382
19	3	37500	10	12	2	-4.13058	19.41749	18.56236
20	19	40000	7	16	4	-6.15035	19.65547	20.91515
21	7	45000	4	12	5	-7.91037	16.80212	19.17215
22	28	45000	4	14	2	-10.9984	23.54697	21.20961
23	8	45000	10	12	2	-9.15824	16.80212	21.61844
24	29	45000	10	14	2	-9.14825	23.54697	20.44553
25	4	37500	10	12	5	-5.16364	13.63487	20.63034
26	26	37500	10	14	2	-6.82671	15.36448	21.9382
27	20	40000	10	16	4	-7.39582	19.65547	20.72424
28	30	45000	4	14	5	-5.59653	17.91247	23.09804
29	31	45000	10	14	5	-8.41429	17.91247	19.828
30	9	45000	4	12	2	-7.12587	22.48206	20.72424
31	21	40000	7	16	4	-2.86842	19.65547	20

3.3 Grey coefficient and grey relation grade.

Greys coefficient (GC) and Grey relation grade (GRG) are the formulation sets on the basis of which the multi variable response optimization is carried out so as to obtain the best fit from the varied number of test cases. The GRG value is used to then rank the reading sets in a descending order. The one set with the lowest rank, but highest GRG value is said to be the optimal set as in table 3.

Table 3. Values of Grey coefficients for all response variables.

S. NO	GRG	RANK	PRESSURE	SOD	N	QOC	GC SR	GC-MRR	GC-C
1	0.444366	27	37500	4	12	5	0.52049	0.333333	0.590653
2	0.486755	19	37500	4	12	2	0.465972	0.52103	0.501406
3	0.63178	5	37500	10	12	2	0.454095	0.52103	1
4	0.463349	25	37500	10	12	5	0.920315	0.352418	0.621447
5	0.486288	20	40000	7	12	4	0.548851	0.433515	0.571253
6	0.459375	26	45000	10	12	5	0.507597	0.428341	0.52626
7	0.622818	6	45000	4	12	5	0.423523	0.428341	0.847731
8	0.562685	12	45000	10	12	2	0.424953	0.428341	0.52626
9	0.612481	7	45000	4	12	2	0.733455	0.698018	0.610946
10	0.495589	18	36000	7	16	4	0.440378	0.477531	0.561868
11	0.719943	2	40000	7	16	1	0.43783	1	0.580846
12	0.503044	17	40000	1	16	4	0.432285	0.531496	0.552683
13	0.470428	23	40000	7	16	4	0.392704	0.531496	0.414903
14	0.546937	13	40000	7	16	4	0.464885	0.531496	0.463067
15	0.642478	4	40000	7	16	4	0.592382	0.531496	0.395939
16	0.610045	9	40000	7	16	4	0.447368	0.531496	0.377852
17	0.418275	31	40000	7	16	5	0.642268	0.450535	0.372004
18	0.436835	29	40000	7	16	4	0.436652	0.531496	0.338633
19	0.529374	15	40000	7	16	4	1	0.531496	0.590653
20	0.563764	11	40000	10	16	4	0.578984	0.531496	0.610946
21	0.522445	16	40000	7	16	4	0.920787	0.531496	0.702507
22	0.477162	22	45000	7	16	4	0.484658	0.613494	0.333333
23	0.436383	30	37500	4	14	5	0.732059	0.390186	0.52626
24	0.540714	14	37500	4	14	2	0.646247	0.596931	0.509526
25	0.716482	3	37500	10	14	5	0.416183	0.596931	0.632198
26	0.466396	24	37500	10	14	2	0.515683	0.390186	0.501406
27	0.484613	21	40000	7	14	4	0.333333	0.477531	0.455818
28	0.571896	10	45000	4	14	2	0.409111	0.791438	0.561868
29	0.722235	1	45000	10	14	2	0.374309	0.791438	0.643208
30	0.442687	28	45000	4	14	5	0.362381	0.463334	0.428076
31	0.611346	8	45000	10	14	5	0.528478	0.463334	0.728434

The above tabulation shows the rank of the various test cases in accordance with Grey relation grade value. The higher this value the much better and optimal is the multi variable response for a given model as in table 4

Table 4. Rank variables based on GRG values.

RANK	GRG	PRESSURE	SOD	ND	QOC
1	0.722235	45000	10	14	2
2	0.719943	40000	7	16	1
3	0.716482	37500	10	14	5
4	0.642478	40000	7	16	4
5	0.63178	37500	10	12	2
6	0.622818	45000	4	12	5
7	0.612481	45000	4	12	2

8	0.611346	45000	10	14	5
9	0.610045	40000	7	16	4
10	0.571896	45000	4	14	2
11	0.563764	40000	10	16	4
12	0.562685	45000	10	12	2
13	0.546937	40000	7	16	4
14	0.540714	37500	4	14	2
15	0.529374	40000	7	16	4
16	0.522445	40000	7	16	4
17	0.503044	40000	1	16	4
18	0.495589	36000	7	16	4
19	0.486755	37500	4	12	2
20	0.486288	40000	7	12	4
21	0.484613	40000	7	14	4
22	0.477162	45000	7	16	4
23	0.470428	40000	7	16	4
24	0.466396	37500	10	14	2
25	0.463349	37500	10	12	5
26	0.459375	45000	10	12	5
27	0.444366	37500	4	12	5
28	0.442687	45000	4	14	5
29	0.436835	40000	7	16	4
30	0.436383	37500	4	14	5
31	0.418275	40000	7	16	5

Also it can be observed that the value of the first ranked test case is GRG = 0.784435.

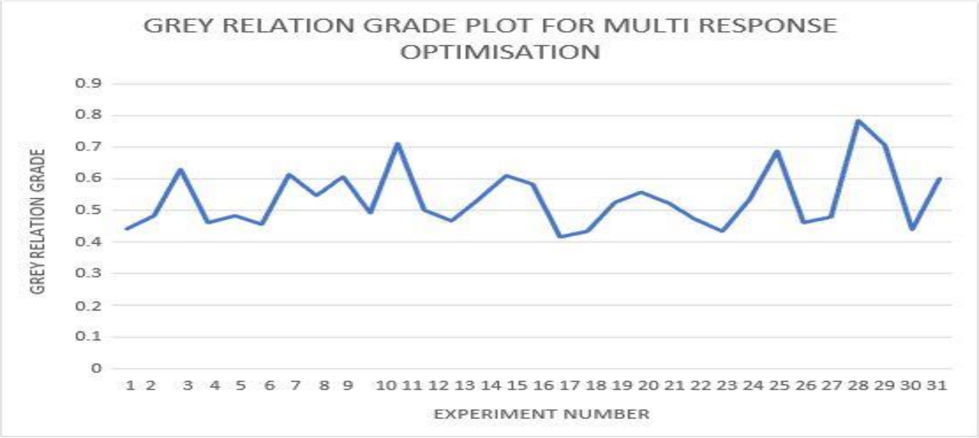

Figure 5. Grey relation plot for multi-response optimization.

The below shown tabulation displays the level values that we have chosen for our project. The levels indicate the lower value, higher value, and the intermediate stage

Table 5. Input Factor Levels.

INPUT FACTORS	LEVEL 1	LEVEL 2	LEVEL 3
PRESSURE	37500 psi	40000 psi	45000 psi
SOD	4mm	7mm	10mm
QOC	2	4	5
ND/MFA	12mm	14mm	16mm

In order to calculate the most influencing factor in our experiment we need to find the mean grey relational grade in our experiment, for all the level, of all the parameters and variables that is list table 5 The levels of each parameter have been assigned a calculated averaged/mean Grey relation grade as in the table 6, which has been found out using the MS Excel program. Using the mean grey relation values at distinct levels we also found out that pressure would be optimal at level 3, standoff distance would be optimal at level 3, quality of cut would be optimal at level 1, and the nozzle diameter would be optimal at level 2 as the respective mean gray values are of the highest level.

Table 6. Mean of Grey Relation Grade.

INPUT FACTORS	LEVEL 1	LEVEL 2	LEVEL 3	DIFF = MAX-MIN
PRESSURE	0.5202015	0.5334206	0.5647426	0.044541095
SOD	0.5179047	0.5261855	0.5774902	0.057288651
QOC	0.5905427	0.5206924	0.5127866	0.077756101
ND/MFA	0.5299884	0.5547501	0.5335629	0.024761672

Table 7. Optimum Input Parameter Level.

PRESSURE	SOD	ND	QOC
45000	10	14	1

It is also observed that the difference between mean Gray relation value ranges is maximum for the Nozzle diameter. Hence due to which we are able to conclude that the Nozzle diameter is the most influencing parameter in our machining process.

3.4 ANOVA – Analysis of variance.

Analysis of variance (ANOVA) tests the hypothesis whether the two or more populations are equal. The importance of one or more factors by comparing the response variable means at the different factor levels can be determined by ANNOVA. The most important statistic in the analysis of variance table is the p-value (P). The p-value for a term asserts the significance of it. If P is less than or equal to the a-level (0.005), then the effect for the term is significant. If P is larger than the a-level, then the effect is not significant.

3.4.1 Response Surface Regression for Surface Roughness.

Table 8. Analysis of Variance for SR.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	14	1.93678	0.138341	4.39	0.003
Linear	4	0.52957	0.132393	4.21	0.016
PRESSURE	1	0.22733	0.227332	7.22	0.016
SOD	1	0.03563	0.035628	1.13	0.303
ND/MFA	1	0.04447	0.044474	1.41	0.252
QOC	1	0.22187	0.221875	7.05	0.017
Square	4	0.12180	0.030450	0.97	0.452
PRESSURE*PRESSURE	1	0.01493	0.014927	0.47	0.501
SOD*SOD	1	0.08996	0.089964	2.86	0.110
ND/MFA*ND/MFA	1	0.00041	0.000407	0.01	0.911
QOC*QOC	1	0.01885	0.018849	0.60	0.450
2-Way Interaction	6	1.09060	0.181767	5.77	0.002
PRESSURE*SOD	1	0.22300	0.222996	7.08	0.017
PRESSURE*ND/MFA	1	0.07273	0.072732	2.31	0.148
PRESSURE*QOC	1	0.02388	0.023882	0.76	0.397
SOD*ND/MFA	1	0.65685	0.656851	20.86	0.000
SOD*QOC	1	0.01224	0.012242	0.39	0.542
ND/MFA*QOC	1	0.09749	0.097486	3.10	0.098

Regression equation for SR in uncoded units –

1.93 + 0.000050 PRESSURE - 0.113 SOD - 0.087 ND/MFA - 0.266 QOC
+ 0.000000 PRESSURE*PRESSURE + 0.00625 SOD*SOD
+ 0.00107 ND/MFA*ND/MFA - 0.0230 QOC*QOC- 0.000008 PRESSURE*SOD - 0.000004 PRESSURE*ND/MFA
+ 0.000005 PRESSURE*QOC+ 0.02212 SOD*ND/MFA + 0.00604 SOD*QOC
+ 0.01713 ND/MFA*QOC

3.4.2 Response Surface Regression for MRR.

Table 9. Analysis of Variance for MRR.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	14	216.773	15.4838	16.45	0.000
Linear	4	122.670	30.6675	32.59	0.000
PRESSURE	1	16.506	16.5059	17.54	0.001
SOD	1	5.265	05.2647	05.59	0.031
ND/MFA	1	15.834	15.8338	16.82	0.001
QOC	1	84.969	84.9686	90.28	0.000
Square	4	31.657	7.9142	8.41	0.001
PRESSURE*PRESSURE	1	0.026	0.0256	0.03	0.871
SOD*SOD	1	0.043	0.0425	0.05	0.834
ND/MFA*ND/MFA	1	29.410	29.4104	31.25	0.000
QOC*QOC	1	9.932	9.9320	10.55	0.005
2-Way Interaction	6	25.599	4.2665	4.53	0.007
PRESSURE*SOD	1	8.269	8.2691	8.79	0.009
PRESSURE*ND/MFA	1	0.053	0.0528	0.06	0.816

PRESSURE*QOC	1	0.259	0.2594	0.28	0.607
SOD*ND/MFA	1	0.878	0.8780	0.93	0.348
SOD*QOC	1	15.669	15.6692	16.65	0.001
ND/MFA*QOC	1	0.192	0.1920	0.20	0.658
Error	16	15.058	0.9411		
Lack-of-Fit	10	15.058	1.5058	1.65242	0.000
Pure Error	6	0.000	0.0000		
Total	30	231.831			

Regression Equation for MRR in Uncoded Units –

MRR = -58.2 + 0.000410 PRESSURE + 0.678 SOD + 8.67 ND/MFA - 5.64 QOC + 0.000000 PRESSURE*PRESSURE - 0.0043 SOD*SOD
- 0.2868 ND/MFA*ND/MFA + 0.527 QOC*QOC-0.000048 PRESSURE*SOD + 0.000004 PRESSURE*ND/MFA - 0.000017 PRESSURE*QOC
+ 0.0256 SsOD*ND/MFA + 0.2161 SOD*QOC - 0.0240 ND/MFA*QOC

3.4.3 Response Surface Regression: for Circularity

Table 10. Analysis of Variance of circularity

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	14	0.002793	0.000200	3.26	0.013
Linear	4	0.001342	0.000336	5.48	0.006
PRESSURE	1	0.000516	0.000516	8.42	0.010
SOD	1	0.000379	0.000379	6.19	0.024
ND/MFA	1	0.000368	0.000368	6.00	0.026
QOC	1	0.000080	0.000080	1.30	0.270
Square	4	0.000501	0.000125	2.04	0.136
PRESSURE*PRESSURE	1	0.000006	0.000006	0.09	0.766
SOD*SOD	1	0.000389	0.000389	6.34	0.023
ND/MFA*ND/MFA	1	0.000024	0.000024	0.40	0.537
QOC*QOC	1	0.000076	0.000076	1.24	0.281
2-Way Interaction	6	0.000752	0.000125	2.05	0.118
PRESSURE*SOD	1	0.000033	0.000033	0.54	0.473
PRESSURE*ND/MFA	1	0.000253	0.000253	4.13	0.059
PRESSURE*QOC	1	0.000128	0.000128	2.09	0.167
SOD*ND/MFA	1	0.000132	0.000132	2.15	0.162
SOD*QOC	1	0.000169	0.000169	2.76	0.116
ND/MFA*QOC	1	0.000013	0.000013	0.21	0.651
Error	16	0.000980	0.000061		
Lack-of-Fit	10	0.000741	0.000074	1.86	0.232
Pure Error	6	0.000239	0.000040		
Total	30	0.003773			

Regression Equation of circularity in Uncoded Units

CIRC = 0.053 + 0.000002 PRESSURE - 0.01811 SOD + 0.0012 ND/MFA + 0.0185 QOC
+ 0.000000 PRESSURE*PRESSURE + 0.000411 SOD*SOD
+ 0.000261 ND/MFA*ND/MFA-0.00146 QOC*QOC + 0.000000 PRESSURE*SOD-0.000000 PRESSURE*ND/MFA-0.000000 PRESSURE*QOC + 0.000313 SOD*ND/MFA
+ 0.000710 SOD*QOC+0.000198 ND/MFA*QOC

The interaction plot for the Material Removal Rate, Surface Roughness, and Circularity was plotted using the Minitab software and they were utilized to understand the interactions between the various input parameters and the corresponding output parameter in figure 6,7 and 8

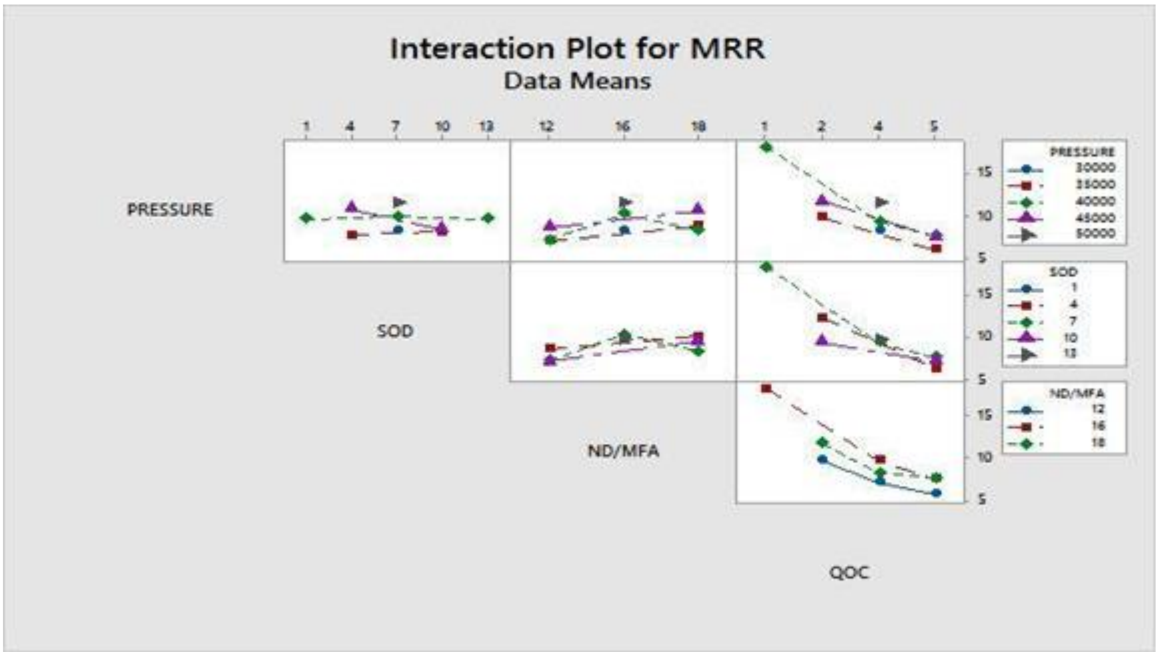

Figure 6. Interaction plot for MRR.

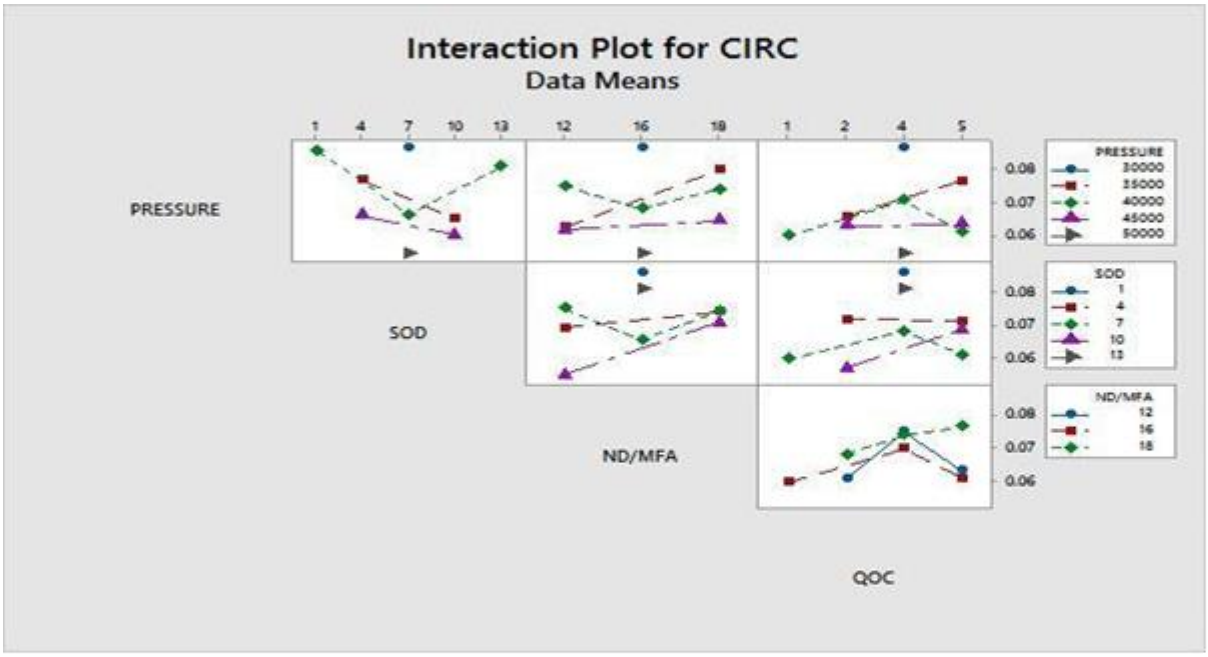

Figure 7. Interaction plot for Circularity

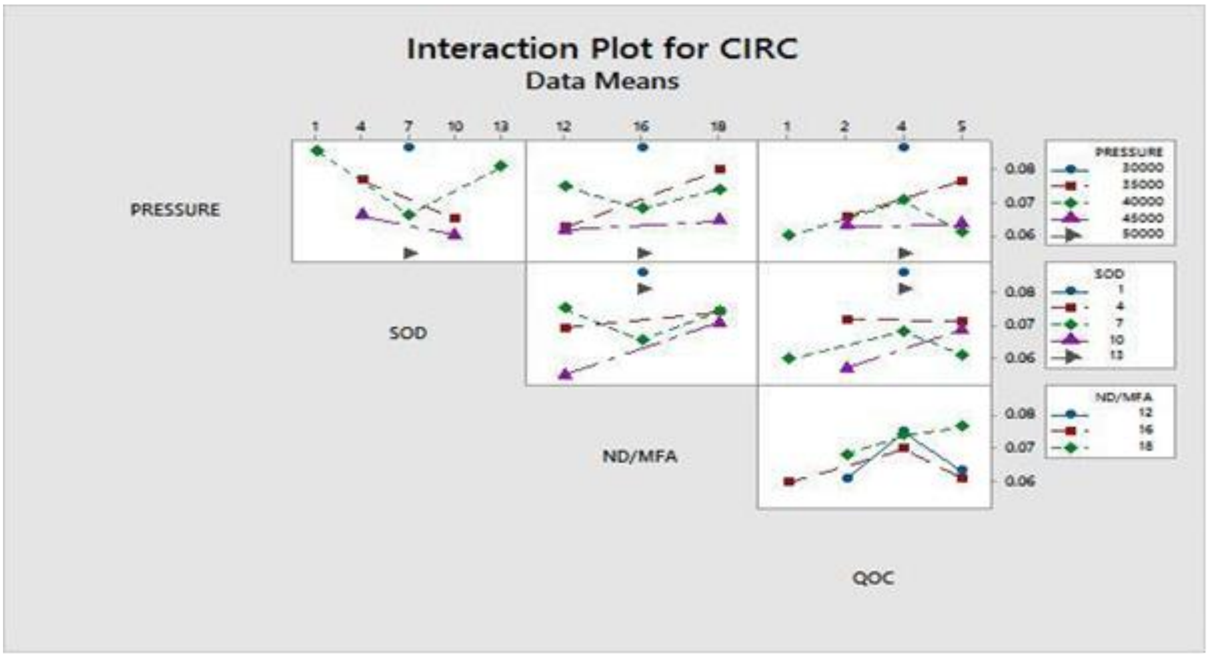

Figure 8. Interaction plot for Surface Roughness.

3.5 Regression equation and model.

In statistical modelling, regression analysis is a statistical process for estimating the relationships among variables. A regression equation is used to predict the value of the required variable with the help of independent variables. Multiple regression is an extension of simple linear regression. It is used when we want to predict the value of a variable based on the value of two or more other variables. The variable we want to predict is called the dependent variable (or sometimes, the outcome, target or criterion variable).

A residual plot is a graph that shows the residuals on the vertical axis and the independent variable on the horizontal axis. If the points in a residual plot are randomly dispersed around the horizontal axis, a linear regression model is appropriate for the data; otherwise, a non-linear model is more appropriate.The residual graphs for MRR and Circularity, and Surface roughness were plotted using the Minitab software and these plots were then used to observe the fitting of the reading obtained to our current model that can be see in figure 9, 10 and 11.

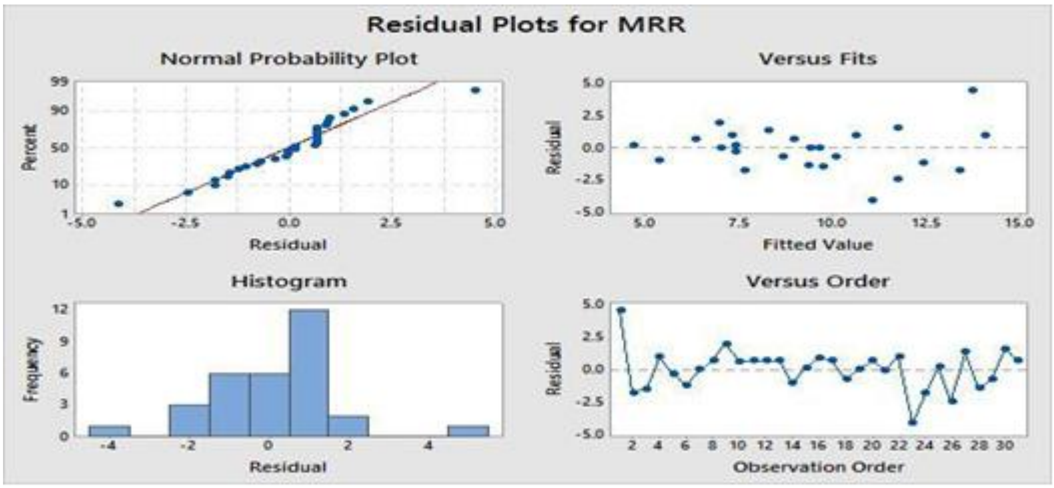

Figure 9. Residual Plots for Material Removal Rate.

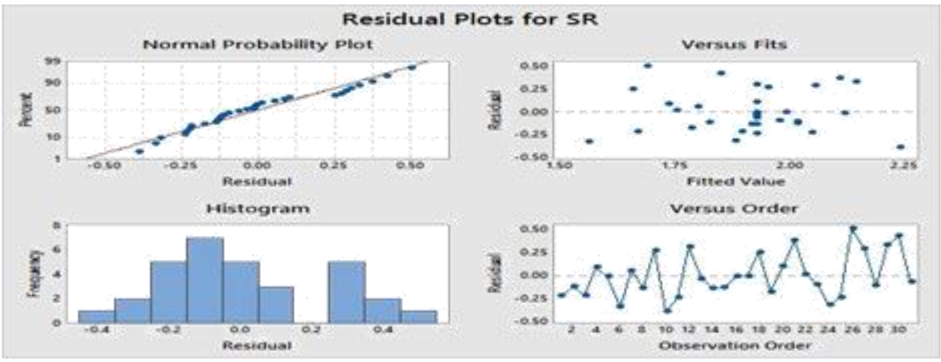

Figure 10. Residual Plots for Circularity.

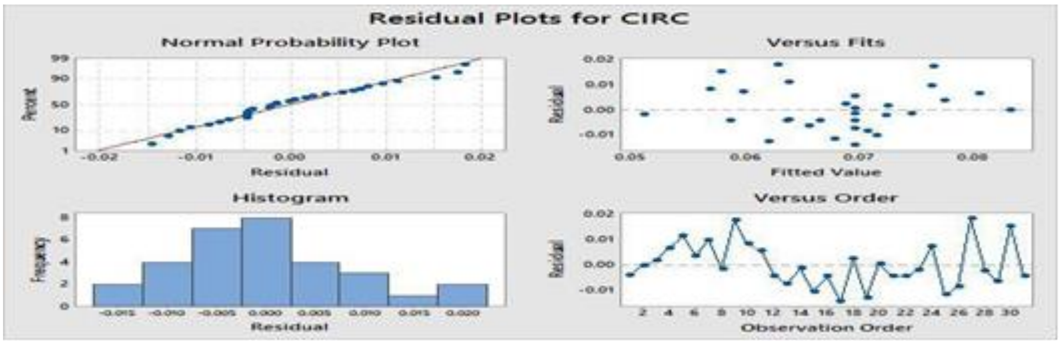

Figure 11. Residual Plots for Circularity.

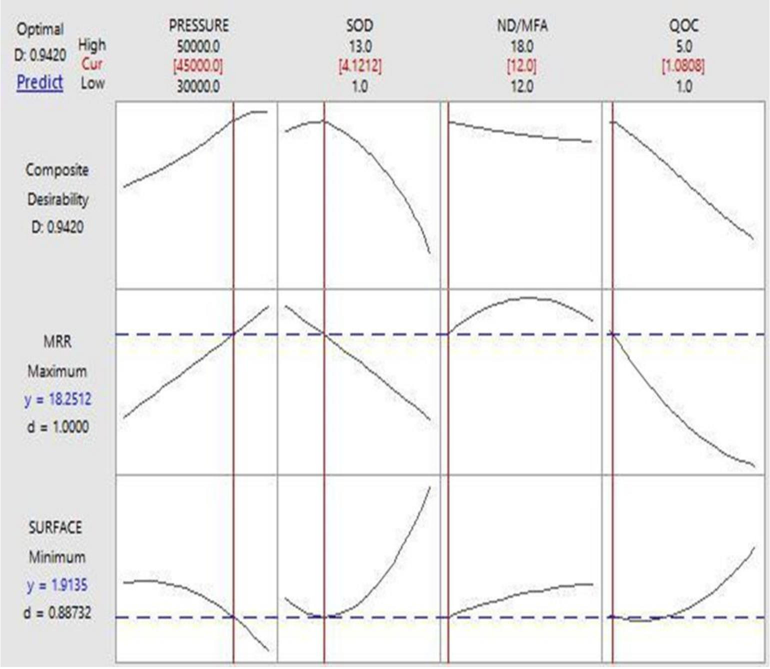

Figure 12. Residual plot for surface roughness.

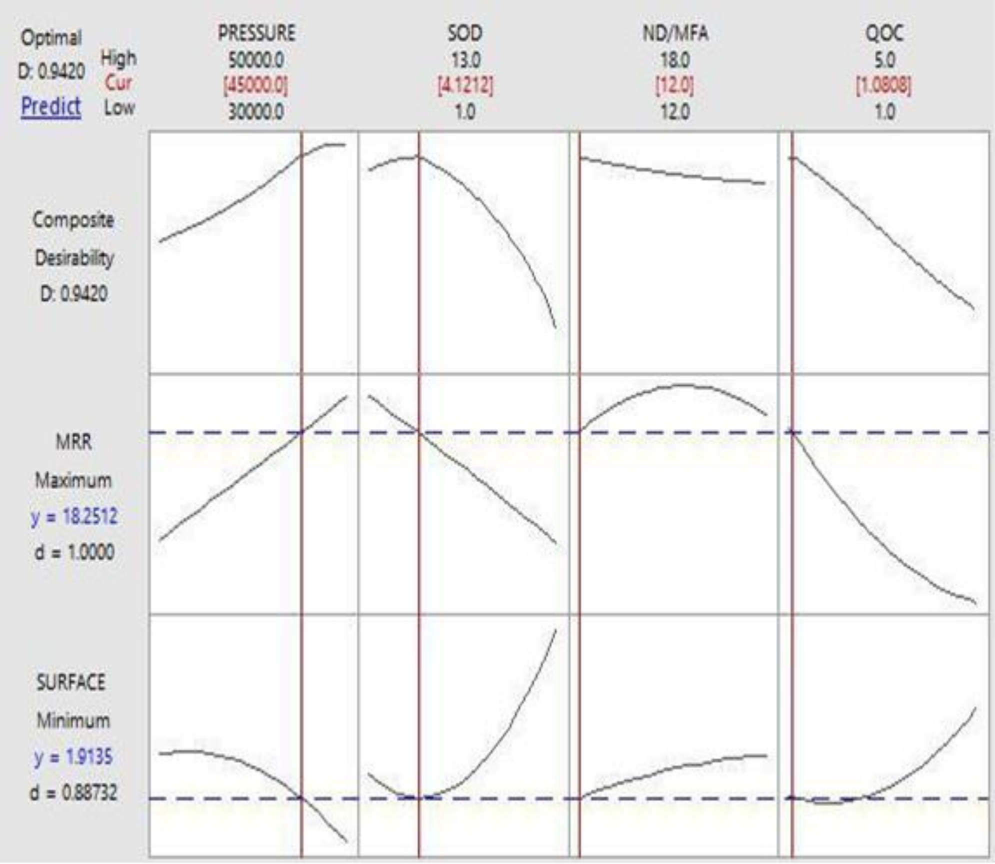

Figure 13. Multi response optimisation predictor graph.

Using the Minitab software we calculated the linear regression equation for the response variables which are as follows-

1. Regression Equation for Surface Roughness –

$$SR = 1.93 + 0.000050P - 0.113S - 0.087N - 0.266Q + 0.000000P*P + 0.00625S*S + 0.00107N*N - 0.0230Q*Q - 0.000008\,P*S - 0.000004P*N + 0.000005\,P*Q + 0.02212\,S*N + 0.00604\,S*Q + 0.01713\,N*Q$$

2. Regression Equation for Material Removal Rate –

$$MRR = -58.2 + 0.000410P + 0.678S + 8.67N - 5.64\,Q + 0.000000\,P*P - 0.0043\,S*S - 0.2868\,N*N + 0.527\,Q*Q -0.000048\,P*S + 0.000004\,P*N - 0.000017\,P*Q + 0.0256\,S*N + 0.2161\,S*Q - 0.0240\,N*Q$$

3. Regression Equation for Circularity –

$$CIRC = 0.053 + 0.000002P -0.01811S + 0.0012N + 0.0185Q + 0.000000P*P + 0.000411S*S + 0.000261N*N - 0.00146Q*Q + 0.000000\,P*S - 0.000000P*N - 0.000000P*Q + 0.000313\,S*N + 0.000710S*Q + 0.000198\,N*Q$$

3.6 Multi response optimisation using anova predictor plot.

Multi response optimisation is the process of determining the optimum value of the input variables by finding the most desirable fit of the output responses that can be see in figure12.

A desirability function is created for each process output, with multiple outputs combined into an overall desirability using adjustable weights for each output. From the graph it can be stated that the multi response optimal process parameters are pressure at 45000 psi, standoff distance at 4 mm, nozzle diameter at 12mm, and quality of cut at 1.

3.7 Conformity test.

Table 11. Conformity table for MRR.

PRESSURE	**SOD**	**N**	**QOC**	**TH MRR**	**EXP MRR**	**ERROR**
45000	4	14	2	15.0435	14.5465	3.303752451

Table 12. Conformity table for SR.

PRESSURE	**SOD**	**N**	**QOC**	**TH SR**	**EXP SR**	**ERROR**
45000	4	14	2	1.5475	1.4812	4.284329564

Table 13. Conformity table for Circularity.

PRESSURE	**SOD**	**N**	**QOC**	**TH CIRC**	**EXP CIRC**	**ERROR**
45000	4	14	2	0.087	0.083	4.597701149

4. Conclusions

In the conclusion for the study, we carried out a conformity test on the work piece in accordance with the Grey relation values obtained. The values of MRR, SR, Circularity were calculated to give their experiment values at the optimal level of input parameters. These values were then compared with the actual theoretical values and the error percentage was found out to be conforming to the 5% standard allowance. The error percentage for material removal rate was found to be at 3.303%, and was well within the error allowance. The error percentage for surface roughness was found to be at 4.28%, and was well within the error allowance. The error percentage for circularity was found to be at 4.597%, and was well within the error allowance.

In this paper an experimental study on material removal rate, surface roughness, circularity by abrasive water jet machining of Monel K400 nickel alloy is presented.The effects of pressure, nozzle diameter, stand-off distance, and quality of cut was studied on MRR, SR, Circularity. Through the due course of the project it was concluded that through the viewpoint of multi variable response optimization techniques like Grey analysis, ANOVA, the Grey rank was found out and this rank denotes the best combination of input parameters. Using the mean grey relation values at distinct levels we concluded that pressure would be optimal at level 3 (45000 psi), standoff distance would be optimal at level 3 (10mm), quality of cut would be optimal at level 1 (1), and the nozzle diameter would be optimal at level 2 (14mm) as their respective mean grey values are of the highest level. It was also observed that the difference between mean Grey relation value ranges is maximum for the quality of cut at 0.075. Due to which we are able to concur that the quality of cut is the most influencing parameter in our machining process. Also using ANOVA MRO predictor plot, in our experiment we have utilized the goal of maximizing the response of MRR value at 18.2512 g/min, as higher is the MRR value, the machining process will be much faster, and as a result the cycle time will be less. At the same time we have also utilized the goal of minimizing the response of Surface Roughness at 1.9135 um so as to obtain a smoother finish and distinct, defined machined surface.Confirmation test done in the optimal parameters list in table 11, 12 and 13.

5. References

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