Study the effect of process parameters in plasma arc cutting on Inconel-625 material by analysis of variance

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Abstract

Aim of present work is to investigate the effects of process parameters of plasma arc cutting of Inconel-625 material using analysis of variance. Three process parameters cutting speed, Arc Voltage and gas pressure are considered and experiments are conducted based on Taguchi L9 Array design. Process responses viz. mean surface roughness (R_a: center line average roughness) and material removal rate (MRR) and Kerf angle of machined surface are measured for each experimental runs. Higher material removal rate means industry can cut more metal in same period of time which ultimately results in more profit. And less surface roughness and Kerf angle makes finished product more suitable for assembly and easy handling. For minimum mean surface roughness and Kerf angle and maximum material removal rate, process parameters are optimized with the help of Taguchi design coupled with S/N ratios method. Analysis of Variance (ANOVA) is performed to get the contribution of process parameters on responses and Mathematical modelling is done by regression analysis. It was found that cutting speed has most significance.

Keywords: **Plasma arc cutting; Inconel 625; Mean surface roughness; Material removal rate; Kerf angle;Regression analysis; ANOVA**

1. Introduction

When heat is added to the solid state of any matter, it converts into liquid state. By adding more heat, it converts into gaseous state. And if further heat is added, it gets converted into plasma state. A plasma is an ionized gas, plasma arc operates typically at temperatures of $10{,}000^0$C -$14{,}000^0$C. Plasma arc cutting (PAC) is a thermal cuttingprocess that makes use of a constricted jet of high-temperature plasma gas to melt and cut metal [1]. The interest of modern industries in plasma arc cutting applications have increased due to the capability of this process to compete with laser cutting (higher quality but also more expensive) and oxygen-fuel cutting (less expensive but lower quality [2]. The plasma arc cutting on the plate is connected by Computer Numerical Control (CNC) system which can reduce cutting time and improve accuracy.

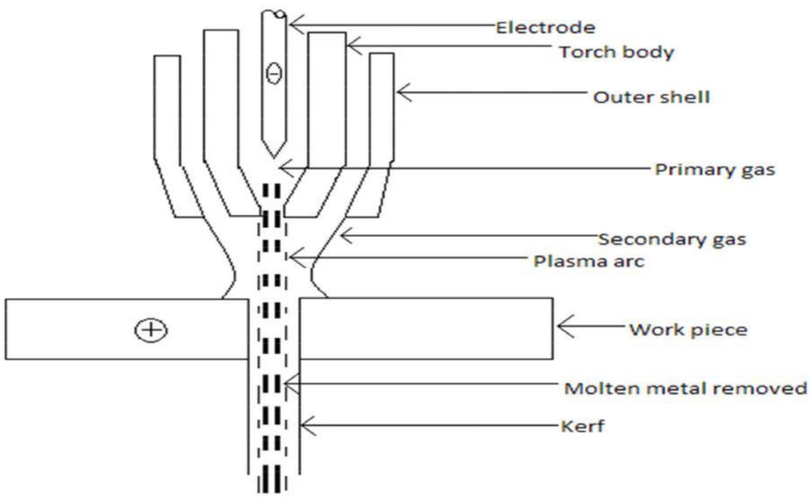

Figure 1. Schematic Diagram of plasma arc cutting [1]

First of all, Plasma arc torch (nozzle) is placed on the plate at some stand-off distance where the cutting will be carried out as shown in figure 1. The torch contains non-melting electrode (cathode). The high temperature plasma cutting gas (primary gas) is impinged on the surface of the work plate(anode) .The arc occurred results in melting of material and partial vaporizing of material due to thermal energy of the arc and cutting gas. Kerf is the width of material removed during the cutting process. The molten metal is removed from the Kerf. The secondary gas is used for cooling purpose.

Significant amount of work has been carried out on various aspects of plasma arc cutting process. Subbarao et al. (2013) [1] have evaluated effect of voltage, cutting speed, plasma gas flow rate on unevenness of cut surface in plasma arc cutting of 12 mm thick plate of Hardox – 400 material. Results of this experiment were analyzed by means of the Analysis of Variance (ANOVA) technique with use of design expert 8.0.7.1 software. Milan Kumar et al. (2014)[3] have considered process parameters as gas pressure, arc current, torch height for experiments based on L_{27} array. Process responses viz. material removal rate and multiple roughness characteristics were optimized using Taguchi method coupled with grey relational analysis. Bhuvenesh et al. (2012)[2] have optimized the process parameters air pressure, cutting current, cutting speed and arc gap with consideration of their effect on material removal rate and surface roughness using Taguchi method in plasma arc cutting of AISI 1017 steel. Gariboldi and Previtali (2004)[4] have taken process parameters as cutting gas and feed rate for experiments on 5 mm thick sheet of titanium. They observed unevenness, kerf width and microstructures of machined surface. They also considered heat affected zone in their investigation. Ilii et al. (2010) [5] have taken process parameters as cutting speed, material thickness and current intensity to study their effect on surface roughness by developing regression equation on plasma arc cutting of SS.

Ali et al. (2016) [6] have done comparative analysis of temperature distribution and surface roughness between Aluminium-19000 and stainless steel 304 using plasma arc cutting process by taking process parameters as current, voltage, velocity of cut and gas pressure. Tsiolikas et al. (2016) [7] have done optimization of cut surface quality during CNC plasma-arc cutting of mild steel plates using design of experiments. The processparameters tested include cutting speed, cutting height and arc voltage. Analysis of means (ANOM) and analysis of variances (ANOVA) were used in order for the effect of each parameter on the surface quality to be assessed.

An extensive review of literature reveals the fact that no research work has been done with high values of cutting speed. So present work considers high cutting speed in plasma arc cutting of Inconel 625 material.

The objective of this research is to determine the effects and optimization of three process parameters as cutting speed, plasma gas pressure and Arc voltage on mean surface roughness and material removal rate in plasma arc cutting of 6 mm thick plate of Inconel 625 material using response surface method. ANOVA coupled with response surface method is performed to check significance of process parameters on responses in this research.

2. Experimental procedure

2.1 Base material

Inconel 625 is corrosion resistant steel. It has optimal combination of hardness, strength and ductility. It is easy to bend, machine and weld [8]. It is having applications in areas like Shipping and Chemical machinery, marine application, knives, feeders, slurry pipe systems, screw conveyor. [8]. Composition of Inconel - 625 is shown in Fig 2.

Nickel	58.0 min.
Chromium	20.0-23.0
Iron	5.0 max.
Molybdenum	8.0-10.0
Niobium (plus Tantalum)	3.15-4.15
Carbon	0.10 max.
Manganese	0.50 max.
Silicon	0.50 max.
Phosphorus	0.015 max.
Sulfur	0.015 max.
Aluminum	0.40 max.
Titanium	0.40 max.
Cobalt[a]	1.0 max.

Figure 2. Composition of Inconel - 625

Figure.3. Experimental Setup

2.2 Experimental setup

Experiments are conducted on the CNC plasma arc cutting machine (Digicut, M.A engineering) as shown in fig3. Air is used as cutting gas. A plate of Inconel 625 having dimensions of 500mm×50mm×6mm was prepared for the experimental work. In this research, three levels of cutting speed (mm/min), three levels of pressure (psi) and three levels of Arc voltage (A) were taken as shown in Table 1.

Design Factors	Units	Notation	Level 1	Level 2	Level 3
Cutting speed	mm/min	A	700	900	1100
Gas pressure	Bar	B	4.2	4.8	5.2
Arc voltage	A	C	50	60	70

Table 1

A plate was cut in 9 pieces (50mm×50mm×6mm) with all combinations of process parameters by computer numerical controlled plasma cutting machine. Experiments were carried out with current setting of 132 volts. The distance between the torch and the plate was 3 mm.

2.3 Material removal rate, surface roughness measurement and Kerf Angle

To measure MRR, the weight was calculated after cutting. Material removal rate (MRR) of plasma arc cutting process was calculated by following formula:

$$MRR = \frac{Change\ in\ Material\ Weight}{Cutting\ Time}$$

Where, MRR: Metal Removal Rate, T: cutting time(s)

Surface roughness was measured by surface roughness tester (Mitutoyo SJ210, Taylor Hobson) as shown in fig 4 and R_a value was considered for 3 sides of cut work-piece because at one side where the plasma flame enters is having slightly irregular surface having some peak of dross formed making impossible to measure R_a value on that side. That peak was forming because of high density of dross accumulation when flame starts suddenly with high intensity making melting of more metal and all of that molten metal could not be carried away by high velocity plasma gas coming out from torch. Mean of R_a values of 3 sides was considered as mean surface roughness in this experiment. Kerf angle is measured with help of vernier caliper with the following equation.

$$\sin \propto = \frac{Thickness\ of\ plate}{Distance\ between\ plate\ at\ bottom}$$

Figure 4. Surface roughness tester (Mitutoyo SJ210, Taylor Hobson)

2.4 Design

Experiment design was done using Taguchi Method. A Taguchi design contains all Best possible combinations of a set of factors. This is the most conservative design approach, and it is also gives the most suitable results in experiment [1]. Authors have randomized experiment run order to remove effect of environment if any as shown in below Table 2

Run Order	Cutting Speed (mm/min)	Gas Pressure (Bar)	Arc voltage (I)	Ra1	Ra2	Ra3	MRR gm/s	Mean Ra	Kerf Angle
1	700	4.2	60	10.48	10.10	9.95	0.138	10.1767	2.76
2	900	4.8	50	13.64	13.84	13.89	0.249	13.7900	1.82
3	1100	5.2	70	10.48	10.01	9.95	0.175	10.1467	1.97
4	900	4.2	60	14.80	14.36	14.22	0.284	14.4600	1.78
5	1100	4.8	50	12.02	11.51	11.14	0.263	11.5567	2.24
6	700	5.2	70	20.82	20.56	20.46	0.110	20.6133	1.65
7	1100	4.2	60	14.20	14.10	14.32	0.175	14.2067	1.52
8	700	4.8	50	13.30	13.30	12.96	0.111	13.1867	1.91
9	900	5.2	70	10.06	9.96	10.20	0.213	10.0733	2.04

Table 2. Experimental results for 6 mm Inconel 625 plate

3. Result and Conclusions

3.1 Analysis of Signal- to- Noise (S/N) ratio

The term signal represents the desirable value (mean) for the output characteristic and the term noise represents the undesirable value (deviation, SD) for the output characteristic. Therefore the S/N ratio is the ratio of the mean to the SD. The S/N ratio is used to measure the quality characteristic deviating from the desired value. Taguchi design chooses to calculate the signal-to-noise ratio for finding effective parameter for desire response value. The S/N ratio is useful in identifying the significant factors. There are several S/N ratios available, depending on the type of the characteristic; lower the better, nominal is best and higher the better. The lower the better characteristic is selected, since lowest value for surface roughness, Kerf angle and Larger is better for MRR.

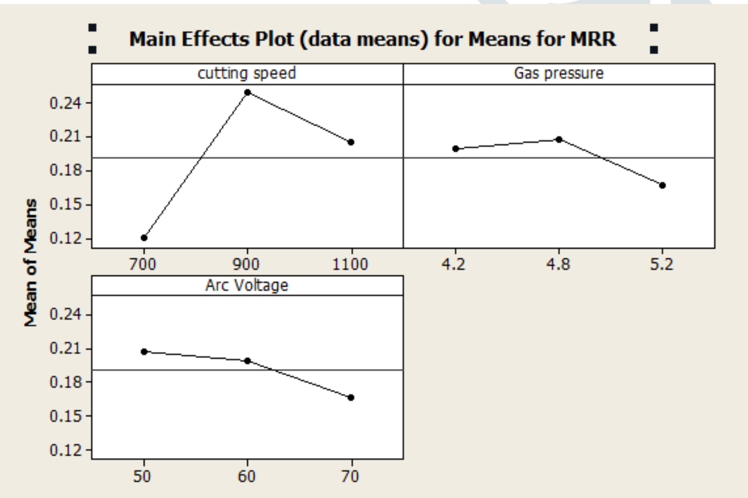

Figure-5 Main effect plot for Means for MRR

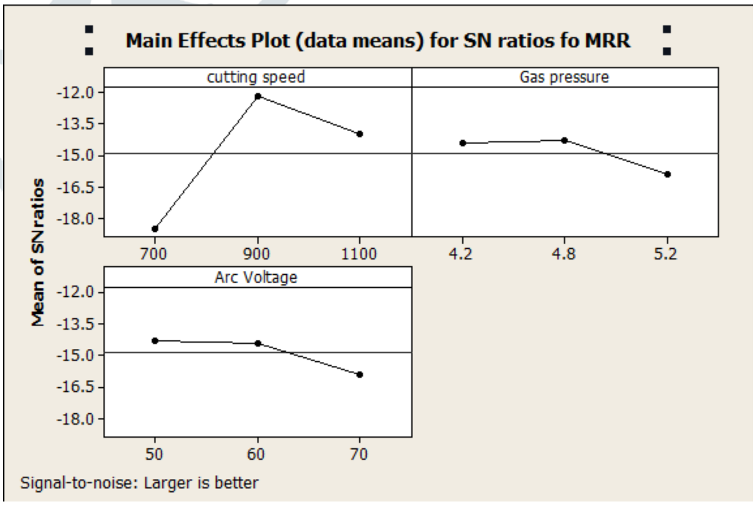

Figure-6 Main effect plot for S/N ratio for MRR

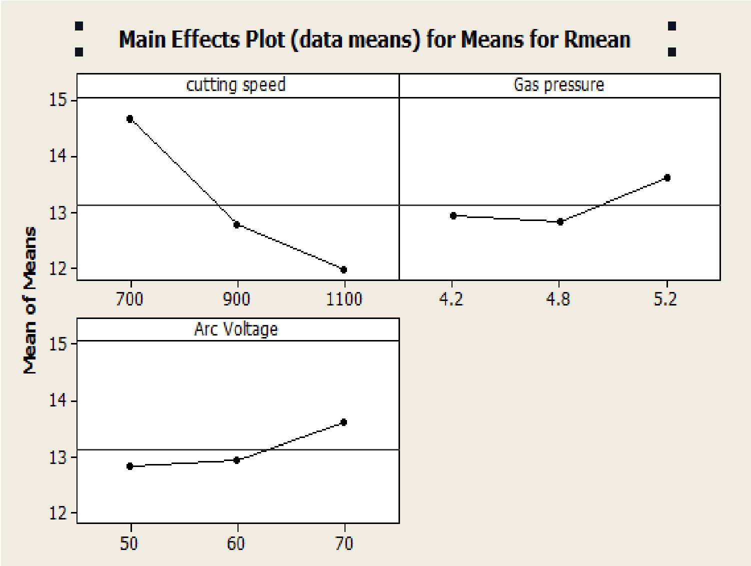

Figure - 7 Main effect plot for means of Rmean

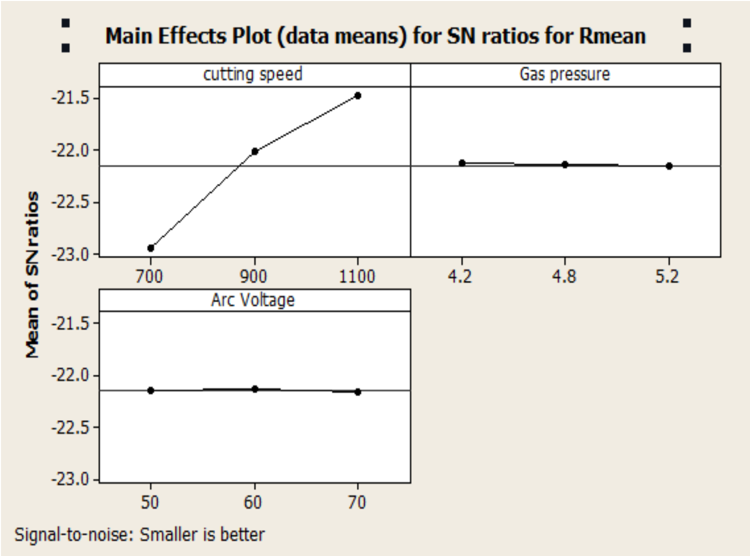

Figure-8 Main effect plot for SN ratios for Rmean

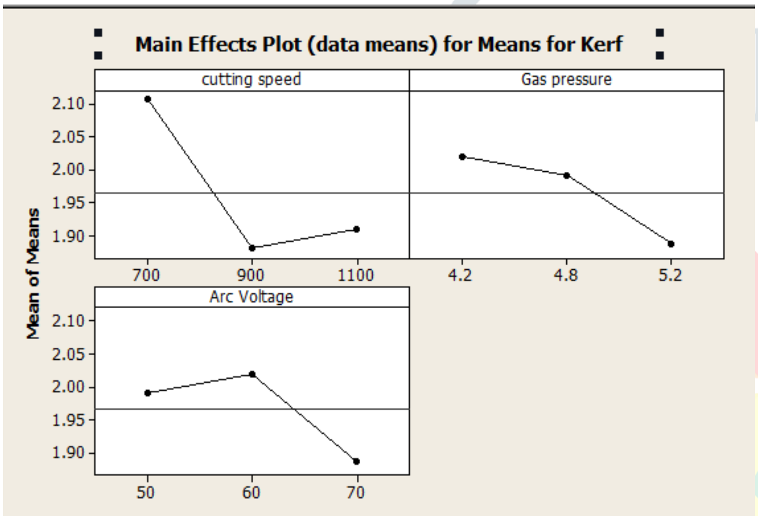

Figure- 9 Main effects plot for means for Kerf angle

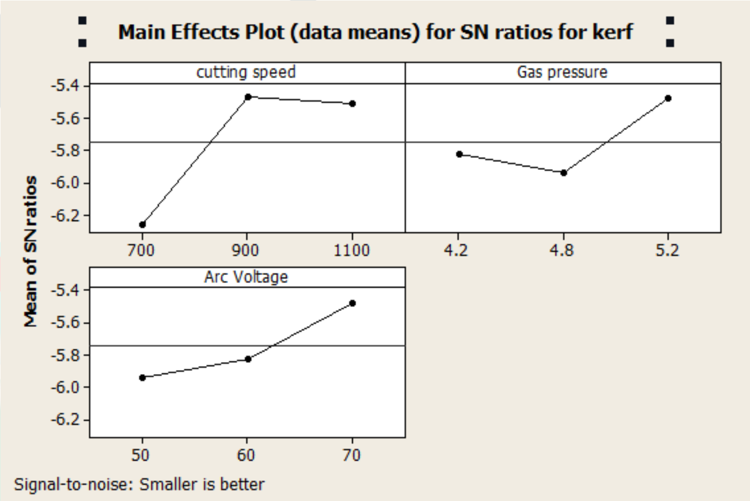

Figure- 10 Main effects plot for SN ratios for Kerf

Figure 5, 6, 7, 8, 9,10 shows the main effect plot for S/N ration and Mean for MRR, R mean and surface roughness. Table 4,5,6 shows total responses for S/N ration for MRR, Rmean and Kerf angle. Highest sum of S/N ratio for different level for factors gives the most significant level for concern factor. From the graph it is evident that MRR increases with increase in cutting speed from 700 mm/min to 900 mm/min whereas thrust MRR decreases with increase in cutting speed from 900 mm/min to 1100 mm/min for surface roughness, surface roughness value increases with increase in Gas pressure from 4.8 bar to 5.2 bar whereas value decreases with increase in cuttting speed from 700 mm/min to 1100mm/min.for Kerf angle, kerf angle value increases with increase in Arc voltage from 60 (I)to 70(I).

Level	Cutting Speed	Gas Pressure	Arc Voltage
1	0.1197	0.1990	**0.2077**
2	**0.2487**	**0.2077**	0.1990
3	0.2043	0.1660	0.1660
Delta	0.1290	0.0417	0.0417
Rank	1	2.5	2.5

Table 3 – Total Response for Signal to Noise Ratio for MRR

Level	Cutting Speed	Gas Pressure	Arc Voltage
1	14.66	12.95	**12.84**
2	12.77	**12.84**	12.95
3	**11.97**	13.61	13.61
Delta	2.96	0.77	0.77
Rank	1	2.5	2.5

Table 4 – Total Response for Signal to Noise Ratio for Surface Roughness

Level	Cutting Speed	Gas Pressure	Arc Voltage
1	**-6.263**	-5.821	**-5.942**
2	-5.467	**-5.942**	-5.821
3	-5.510	-5.477	-5.477
Delta	0.795	0.465	0.465
Rank	1	2.5	2.5

Table 5 – Total Response for Signal to Noise Ratio for Kerf Angle

As smaller-the-better was selected for surface roughness and Kerf Angle the lowest values at all levels were evaluated to determine the optimal combination of cutting speed, Gas Pressure and Arc Voltage. Therefore, the optimum combination available for MRR is A2-B2-C1, for surface roughness A3-B2-C1 and for Kerf Angle A1-B2-C1.

3.2 Anova Method

Analysis of Variance (ANOVA) is performed using Design Expert 10.0.3 software for each response to check significance of factors on each response. ANOVA for material removal rate is as shown in Table 4 and ANOVA for mean surface roughness is as shown in Table 5. These tables also show the Degrees of Freedom (DOF), sum of squares, mean squares, F-values and P-value. ANOVA analysis is done with 95% confidence level.

Factor	DF	SS	MS	F	%
Cutting Speed	2	0.02577	0.01289	9.44	**14**
Gas Pressure	2	0.00290	0.00145	0.28	**76.5**
Arc Voltage	2	0.0275	0.015	0.95	**2.05**
Error	0	0	-	-	-
Total	6	0.5617	0.02934	-	-
Pooled	0.0369	0.07195	0.7195	-	-

Table -6 % of contribution of factor towards response for MRR

Factor	DF	SS	MS	F	%
Cutting Speed	2	11.4	5.7	0.44	**66.1**
Gas Pressure	2	1.0	0.5	0.04	**9.65**
Arc Voltage	2	2.53	0.45	0.65	**26.23**
Error	0	0	-	-	-
Total	6	14.93	6.65	-	-
Pooled	3.51	3.86	3.69	-	-

Table -7 % of contribution of factor towards response for Surface Roughness

Factor	DF	SS	MS	F	%
Cutting Speed	2	0.091	0.045	0.28	**76.1**
Gas Pressure	2	0.029	0.015	0.08	**9.92**
Arc Voltage	2	0.269	0.042	0.029	**14.95**
Error	0	0	-	-	-
Total	6	14.93	6.65	-	-
Pooled	0.4162	0.4536	0.489	-	-

Table -8 % of contribution of factor towards response for Kerf Angle

ANOVA values of experimental results for the MRR, surface roughness and Kerf Angle are shown in table 6, 7, 8. The significance of control factors in ANOVA is determined by comparing F values of each control factor. For MRR, control factors A, B and C have 14%, 76.5% and 2.05% contribution respectively. For surface roughness, control factors A, B and C have 66.1%, 9.63% and 26.23% contribution respectively. For circularity, control factors A, B and C have 76.1%, 9.92% and 14.95% contribution respectively. In general for MRR cutting speed is most significant factor whereas for surface roughness and Kerf Angle cutting speed and arc voltage is most significant parameters respectively

3.3 Regression Analysis

Mathematical models based on cutting parameters, such as drill tool, cutting speed and feed rate were obtained from regression analysis using MINITAB 14 statistical software to predict MRR, Surface Roughness and Kerf Angle. The model equation is as follows for each response. Statistically obtained linear relationship between response and parameters are statistically significant. Theoretical value obtained from this relationship varies only by 2 to 3% maximum.

3.3.1 Regression Analysis: MRR versus cutting speed, Gas pressure, Arc Voltage

The regression equation is

MRR = 0.179 + 0.000212 cutting speed - 0.0152 Gas pressure - 0.00178 Arc Voltage

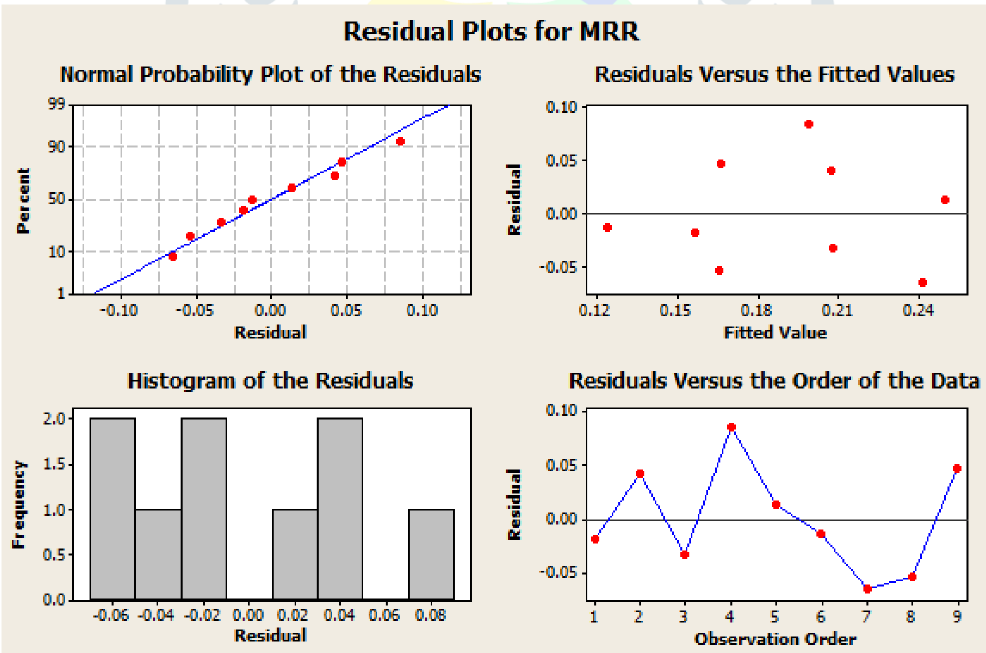

Figure 11. MRR versus cutting speed, Gas pressure, Arc Voltage

3.3.2 Regression Analysis: Rmean versus cutting speed, Gas pressure and Arc Voltage

The regression equation is
Rmean = 15.6 - 0.00672 cutting speed + 0.35 Gas pressure + 0.031 Arc Voltage

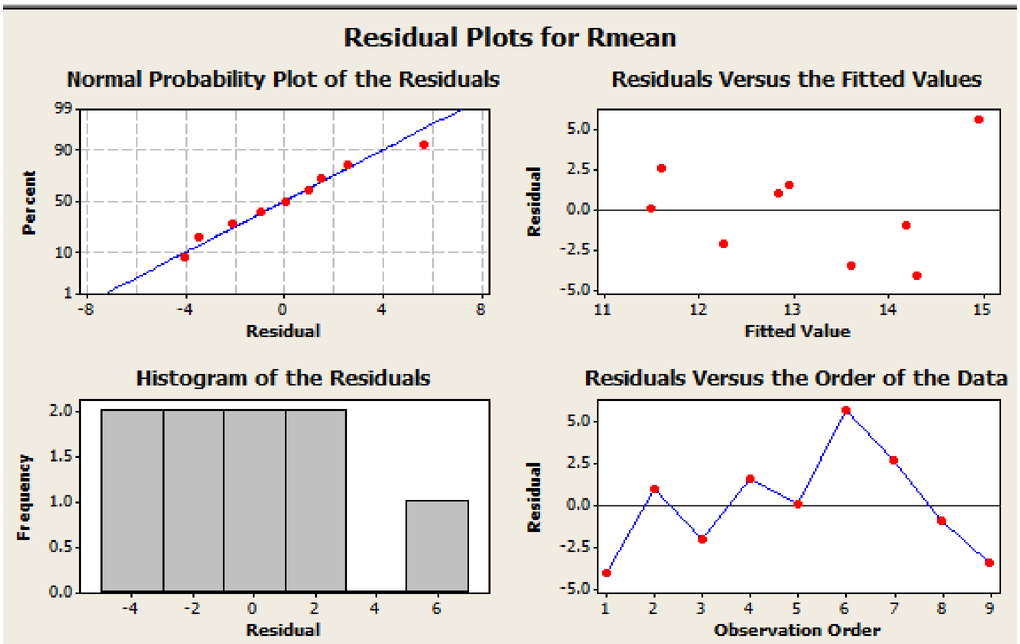

Figure 12. Rmean versus cutting speed, Gas pressure and Arc Voltage

3.3.3 Regression Analysis: Kerf versus cutting speed, Gas pressure, Arc Voltage

The regression equation is
Kerf = 3.08 - 0.000492 cutting speed - 0.102 Gas pressure - 0.0031 Arc Voltage

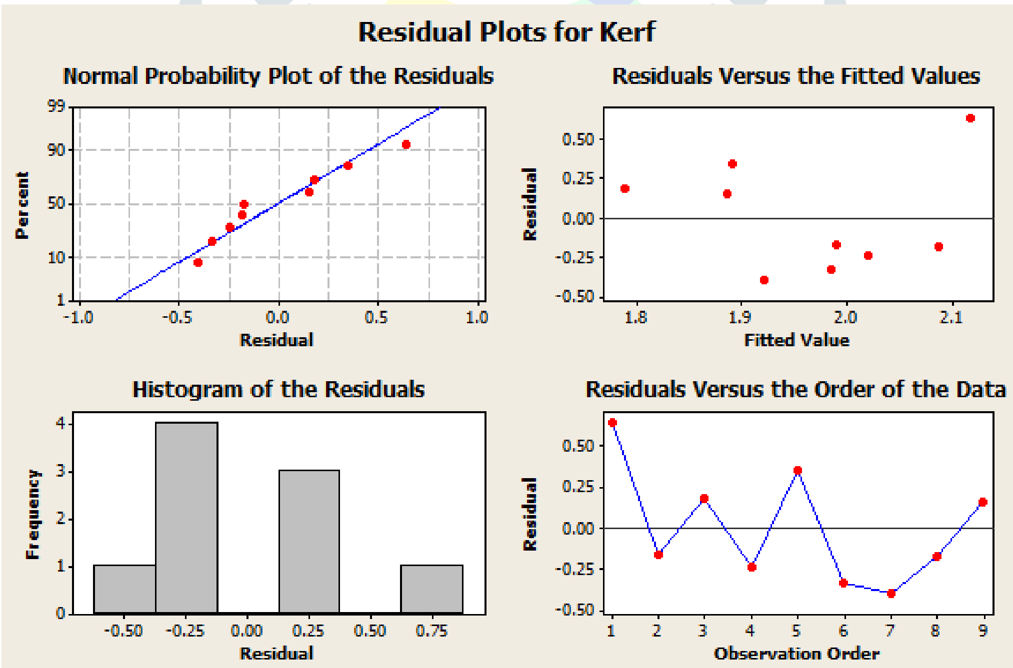

Figure 13. Kerf versus cutting speed, Gas pressure, Arc Voltage

IV. CONCLUSIONS

This paper presents investigation on effect and optimization of process parameters on MRR and mean surface roughness and Kerf Angle with the help of ANOVA coupled with regression analysis method.

For MRR, control factors A, B and C have 14%, 76.5% and 2.05% contribution respectively. For surface roughness, control factors A, B and C have 66.1%, 9.63% and 26.23% contribution respectively. For circularity, control factors A, B and C have 76.1%, 9.92% and 14.95% contribution respectively. In general for MRR cutting speed is most significant factor whereas for surface roughness and Kerf Angle cutting speed and arc voltage is most significant parameters respectively.

Material removal rate increases with increase of cutting speed and mean surface roughness decreases with increase of cutting speed and Kerf angle increasing with increasing Arc Voltage.

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