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Effect of Process Parameters on Surface Roughness and Kerf Width of Mild Steel during Plasma Arc Cutting Using Response Surface Methodology

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Abstract- This study investigated the effects of process parameters of plasma arc cutting (PAC) of low carbon steel material using analysis of variance. Three process parameters, cutting speed, cutting current and gas pressure were considered and experiments were conducted based on response surface methodology (RSM) via the box-Behnken approach. Process responses viz. surface roughness (Ra) and kerf width of cut surface were measured for each experimental run. Analysis of Variance (ANOVA) was performed to get the contribution of process parameters on responses. Cutting current has the most significant effect of 33.43% on the surface roughness and gas pressure has the most significant effect on kerf width of 41.99%. For minimum surface roughness and minimum kerf width, process parameters were optimized using the RSM.

Keywords: Cutting speed, cutting current, gas pressure, surface roughness, kerf width

1 INTRODUCTION

Plasma can be said to be the forth state of matter, it is an ionized gas and the plasma arc operates at temperatures as high as 30,000ºC. When a solid is heated to a certain temperature a change of state occurs and the solid is converted to liquid, when the liquid is heated it transforms into a gaseous state and when the gas is heated further, it gets converted into a plasma state (Patel *et al*., 2017). Plasma cutting is a thermal cutting techniques which can be used to cut several types of electrically conductible materials, this techniques can be applied in several fields of engineering including ship building, bridge building and the welded structures of industrial plants (Pawar and Inamdar, 2016). The use of plasma arc cutting (PAC) offers several advantages over other thermal cutting techniques with respect to cutting speed and cost when compared to oxy-fuel cutting and water jet cutting, also, plasma arc cutting has the capability to cut through the greater metal thickness when compared to the laser beam cutting technique.

The PAC process can be employed in the cutting of mild steel, stainless steel, high hardness and high melting point metals and other metals which are difficult to machine. In plasma cutting a stream of gas jet in the plasma melts and removes the material from the kerf that is generated. During the process an electric arc burns between an electrode and the workpiece, the electrode tip is placed in a water- or air-cooled nozzle in the torch. The plasma gas is conducted through the nozzle, the arc and the plasma gas are forced to pass through a very narrow orifice in the tip of the nozzle and gas is heated and ionized. When the plasma jet hits the workpiece, the heat is transferred due to recombination (the gas reverts to its normal state). The material melts and is expelled from the kerf by a flow of gas. To initiate the process, and ionize the gas, a pilot arc must be generated. The pilot arc heats the plasma gas and ionizes it. Since the electrical resistance of the main arc is lower than that of the pilot arc, the main arc ignites and the pilot arc automatically extinguishes (Duplák, 2019; Bidajwala and Trivedi, 2014).

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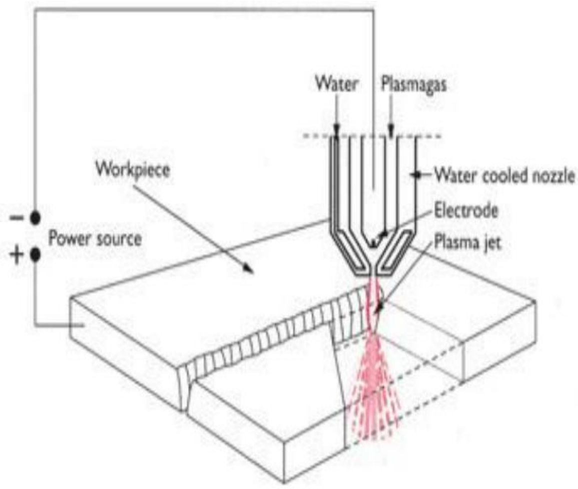

Fig. 1: Principle of Plasma Arc Cutting (Patel *et al*., 2017)

The principle of plasma arc cutting is shown in Figure 1. The basic principle of PAC is that the arc formed between the electrode and the workpiece is constricted by a fine bore copper nozzle, this increases the temperature and velocity of plasma coming from the nozzle. The plasma gas flow is increased during cutting so that the penetration is deep and plasma jet cuts through material and molten material is removed in the efflux plasma.

Plasma cutting is essentially controlled by the operators' empirical mind-set which is typically a result of the recommendations given by the manufacturers of the cutting torches that are to be used. Those recommendations, however, reflect the point of view of the manufacturers' business, which includes not only selling the cutting torches but also the consumables, yet, the manufacturers' recommendations usually lead to solutions that are technically sound in terms of cutting quality, but do not necessarily correspond to the most cost-effective solutions on the user's point of view. As a result, the user customarily attempts to improve the cutting operations by trial-and-error every time it is needed to setup the existing equipment for a new different task (Bidajwala and Trivedi, 2014). This

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procedure is relatively efficient when used by experienced operators, but it is not a quantified optimization process. Therefore, it does not allow a repetition for further usage of the knowledge that was acquired in this manner.

This shortcoming can be avoided through the use of design of experiments (DOE), as a means of attaining empirical mathematical expressions that can be used to predict the optimal process parameters in cutting operations that have not yet been performed. Bidajwala and Trivedi~~,~~ (2014) carried out a review of the parametric optimization of SS 304L using plasma arc cutting. It was noted that the operating conditions in plasma arc cutting have to be carefully optimized through parameter adjustment in order to obtain top quality results with reference to the most recent standard, therefore, failure investigation can focus on the further issue of plasma arc cutting technology i.e. selecting the machining parameter which causes decrease in the surface roughness and increase the metal removal rate. In the work of Adalarasan *et al.* (2014), Grey Taguchi-based responses surface methodology (GT-RSM) was used for the optimization of the plasma arc cutting parameters of 304L stainless steel, The results of the experiment showed that a cutting speed of 2335 mm/min was desired to produce a better response as higher cutting speeds produced a wandering arc which creates a deviation of the arc from the torch and also produces a larger kerf which reduces the quality of the surface produced since the compressed air provides the oxidizing medium which allows the usage of slightly higher cutting speeds without affecting the finish of cut surface in heavier sections.

Maity and Bagal (2015) investigated the effect of process parameters on cut quality of stainless steel of the plasma arc cutting system using the hybrid approach. The result showed that the grey relational grade was significantly affected by the machine parameters directly as well as some interactions. The objective of this research is to investigate the effect of plasma arc cutting parameters on the quality of low carbon steel material of thickness 5 mm using design of experiment via the response surface methodology to determine the experimental pattern. Analysis of variance is also performed to check the significance of the process parameters on the responses.

2 Materials and Methods

2.1 Materials

The base material used in this study is low carbon steel of 5 mm. It is the most widely used type of steel as a result of its cost effectiveness, it contains 0.05-0.25% carbon which makes it malleable and ductile with suitable application in general purpose engineering and construction.

2.2 Experimental Design

In this study, the experimental design used is the response surface methodology of the design of experiment. Three process parameters "cutting speed, cutting current and gas pressure" were used The Box-Behnken approach of the response surface methodology was selected for this research over the central composite design because Box-Behnken requires three different levels for three factors and a total of fifteen experimental runs which is significantly easier for DOE as less time will be required, and the runs do not include factors outside the minimum/maximum values of the study area. The number of runs required for 3 factors are 15 runs as prescribed by the DOE. The cutting operation was performed at Prototype Engineering Development Institute, Ilesha, Osun State, Nigeria, using the Hyperthem Powermax 1650 plasma cutting machine. The independent variable selected are the cutting speed, cutting current and gas pressure as shown in the Table 1.

Table 1. Factor levels for process parameters.

Variables	Unit	Coded Level		
		L_1	L_2	L_3
Cutting Speed CS	mm/m	1000	1500	2000
Cutting Current CC	A	60	80	100
Gas Pressure GP	Bar	5.5	6.0	6.5

Table 2 Experimental design matrix

Runs	CS (mm/min)	CC (A)	GP (bar)	CS	CC	GP
1	-1	-1	0	1000	60	5.5
2	1	-1	0	2000	60	5.5
3	-1	1	0	1000	100	5.5
4	1	1	0	2000	100	5.5
5	-1	0	-1	1000	80	5.0
6	1	0	-1	2000	80	5.0
7	-1	0	1	1000	80	6.0
8	1	0	1	2000	80	6.0
9	0	-1	-1	1500	60	5.0
10	0	1	-1	1500	100	5.0
11	0	-1	1	1500	60	6.0
12	0	1	1	1500	100	6.0
13	0	0	0	1500	80	5.5
14	0	0	0	1500	80	5.5
15	0	0	0	1500	80	5.5

A total of 15 runs as shown in Table 2 was carried out without blocks or repetition. The experimental design consists of 3 variables at three levels which are low (-1), medium (0) and high (1). The design of the numbers of experimental runs are shown in Table 1.

2.3 Experimental Setup

The cutting of low carbon steel was conducted as specified by the experimental design. All experiments were performed on a CNC plasma cutting system 'Hyperthem Powermax 1650 CNC Plasma cutting machine' with a dual flow torch as shown in Figure 2. The cuts were performed on a 5 mm thickness of the low carbon steel sheets, with the use of oxygen as plasma gas and air as shielding gas. The specimens were made up of a linear cut 150 mm in length and a rectangular cut of 100 mm side, in order for the cut surface roughness and the kerf width to be measured. For the surface roughness and kerf width measurement every experiment was conducted once, while three measurements were taken along the cut approximately in the middle of the workpiece thickness and the average value of all three measurements was used and treated as the result of a single experiment.

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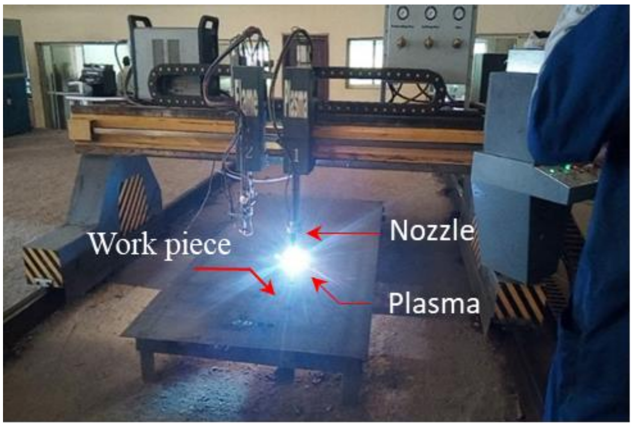

Fig. 2: Plasma cutting machine and workpiece

SRT-6200 surface roughness tester was used to measure the surface roughness, while a Digimatic Vernier caliper was used to measure the kerf width. Analysis of variance (ANOVA) was performed using Minitab 17 software for each of the response to check the significance of each process parameter on the quality. The ANOVA was done with the 90% confidence interval as prescribed by Meyers *et. al*. 2009)

3 Results and Discussion

3.1 Signal to Noise (S/N) Ratio

The signal to noise ratio was calculated for the surface roughness and the kerf width. Signal to noise ratio characteristic equation of "the smaller the better" utilized in this study, because a lesser surface roughness and kerf width are required. The signal to noise ratio was used to generate the main effect plot for each individual response in order to generate the optimized value for each individual response. The signal to noise ratio can be defined as presented in equation 1:

$$S/N = -10 \text{ x } log\left(\frac{1}{N}\sum_{j=1}^{N}\frac{1}{y_{ij}^2}\right) \tag{1}$$

where i is the number of experiments, y is the observed data, n is the number of observations and j is the trial number. Equation (1) represents S/N ratio for smaller the better responses.

3.2 Analysis of Variance

ANOVA for surface roughness is shown in Table 4 and ANOVA for Kerf Width is shown in Table 5. These tables also showed each input contributions to the responses, degrees of freedom, sum of squares, mean square, F-value and P-Value.

Table 3 shows the result of measure data obtained for the surface roughness and kerf width and their calculated signal to noise ratio respectively. The smaller the better-quality characteristics shown in equation 1 were used to calculate the signal to noise for both the surface roughness and hardness respectively. It was observed, from the experimental result presented in Table 3, that the input parameters affected surface roughness and kerf width of low carbon steel using the CNC plasma cutting machine. It was discovered that at higher cutting speed, the surface roughness and hardness increases and this is because an increase in cutting speed causes the flame to spread more across the cut surface. The more time the flame stays on the surface of cut material, the more irregularities are observed on the surface, also, an increase in the cutting current increases the surface roughness which is as a result of the extra energy needed to perform the cutting operation. The surface of the cut was also exposed to more heat due to the extra energy causing the microstructure of the cut region to change. A low current indicates a low cutting energy

. Table 3. Experimental Results and Signal to Noise Ratio

Runs	Input					S/N Ratio	
	CS (mm/min)	CC (A)	GP (bar)	SR (μm)	KW (mm)	SR	KW
1	1000	60	5.5	2.49	2.02	-7.93	-6.11
2	2000	60	5.5	2.56	2.19	-8.17	-6.81
3	1000	100	5.5	2.59	2.78	-8.27	-8.88
4	2000	100	5.5	2.00	2.49	-6.02	-7.92
5	1000	80	5.0	2.21	2.52	-6.89	-8.01
6	2000	80	5.0	2.48	2.29	-7.89	-7.20
7	1000	80	6.0	1.30	2.58	-2.28	-8.23
8	2000	80	6.0	2.64	2.34	-8.43	-7.38
9	1500	60	5.0	2.10	2.38	-6.44	-7.53
10	1500	100	5.0	2.30	3.14	-7.24	-9.94
11	1500	60	6.0	2.19	2.30	-6.81	-7.24
12	1500	100	6.0	1.56	2.40	-3.86	-7.60
13	1500	80	5.5	1.80	2.47	-5.11	-7.85
14	1500	80	5.5	1.86	2.53	-5.39	-8.06
15	1500	80	5.5	1.78	2.44	-5.01	-7.75

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Table 4. ANOVA for Surface Roughness

Factor	DOF	SS	MS	F	P
CS	2	1.03	0.52	17.39	27.97
CC	2	1.23	0.62	20.78	33.43
GP	2	1.19	0.59	19.99	32.16
Error	8	0.24	0.03		6.43
Total	14	3.69	0.26		100
S = 0.453657		R-sq = 72.17 %		R-sq (adj) = 52.07 %	

Table 5. ANOVA for Kerf Width

Factor	DOF	SS	MS	F	P
CS	2	0.23	0.12	11.48	22.62
CC	2	0.28	0.14	13.96	27.51
GP	2	0.43	0.22	21.31	41.99
Error	8	0.08	0.01		7.88
Total	14	1.03	0.07		100
S = 0.263323		R-sq = 66.33%		R-sq (adj)= 54.73%	

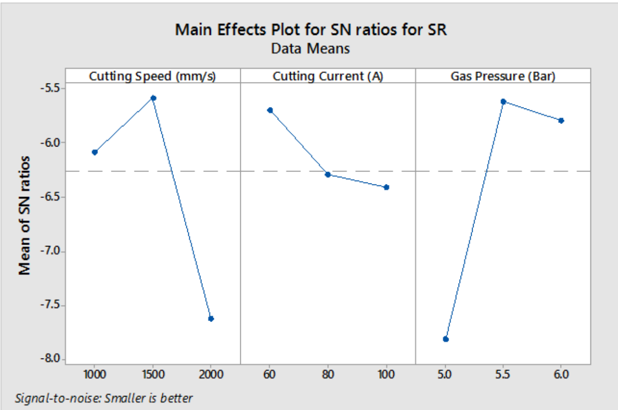

Fig. 3: Main effect plot for surface roughness

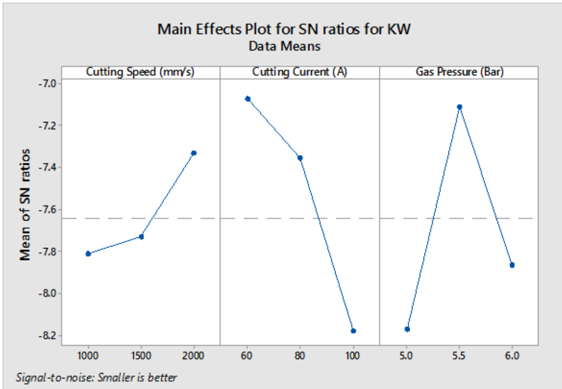

Fig. 4: Main effect plot for kerf width

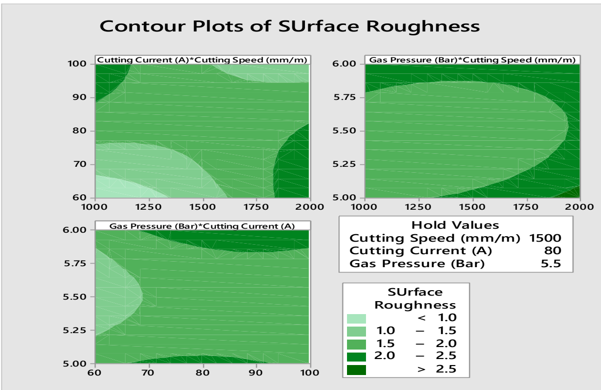

Fig. 5: Contour plot for surface roughness

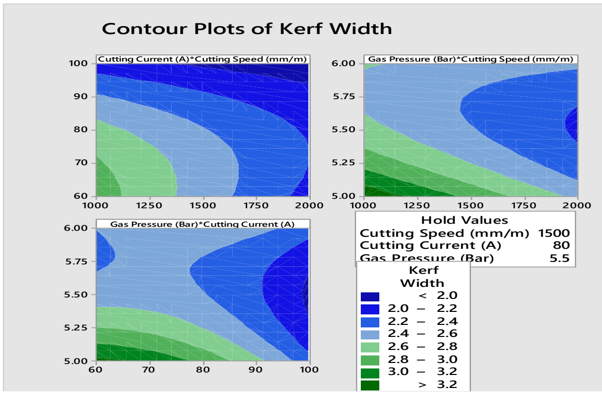

Fig. 6: Contour plot for kerf width

Table 4 shows that the cutting current has the most significant effect of 33.43% on the surface roughness, while the gas pressure and the cutting speed have the following effect, 32.16% and 27.98% respectively. When the cutting speed is increased beyond a certain limit, the cutting torch moves too fast for the plasma arc to maintain its stability, therefore, the plasma arc cannot remain perpendicular to the cutting front, resulting in the formation of surface waves on the cutting surface. Table 5 shows that the gas pressure is the most significant parameter which affects the kerf width having a P value of 41.99% followed by the current with a P value of 27.51% and the least significant parameter is the cutting speed with P value of 22.62%. With increase in pressure, kerf width increases as a result of the excessive pressure which gives a cooling effect rather than blowing the molten material from the workpiece. It can be observed from Figure 3 that the optimum values for the surface roughness is obtained at CS of 2000 mm/min, CC of 100 A and GP of 5.0 bar. This implies that the height of the nozzle when the current was at 100 A is sufficient for the gas pressure of 5.0 bar to blow out the melted portion

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without heating the material (Ferreira *et al*. 2009). In order to obtain the optimum process parameter for the kerf width as observed from Figure 5, a CS of 1000 mm/min, CC of 100 A and a GP of 5.0 bar will be required. This implies that sufficient gas pressure of 5.0 bar was supplied at 100 A and 1000 mm/m to enable cutting and blowing away of the molten material without wastages there by reducing the amount of heat that may affect the workpiece.

Figure 4 shows the effect of CS and CC, CS and GP, CC and GP on the SR. The SR reduces by reducing the value of the CS and increasing the value of the CC while holding the GP at 5.5 bar, also, the SR is reduced by reducing the CS and reducing the GP while holding the CC at 80 A, the last combination will result to a decrease of the SR when the CC is reduced and the GP is reduced while holding the CS at 1500 mm/min. Figure 6 shows contour based interactions analysis between the various input parameters on the kerf width. It can be observed that there was a significant interaction between the CC and CS in the first graph and GP and CS in the second graph due to the elliptical nature of the contour plots.

3.3 Development of Empirical Model

For the optimization of the surface roughness and kerf width, the empirical model equations 2 & 3 which were developed from Minitab 17 software was used;

$$\text{Surface Roughness } (\mu m) = 0.38 + 0.0000496\,CS + 0.0188\,CC - 0.096\,GP \tag{2}$$

$$\text{Kerf Width } (mm) = 3.41 - 0.000238\,CS - 0.00659\,CC - 0.197\,GP \tag{3}$$

4 Conclusion

In this study the experiment and analysis were conducted to determine the effect of cutting parameters on the surface roughness and kerf width of low carbon steel. The study showed that the cutting current has the most significant effect of 33.43% on the surface roughness followed by gas pressure and the cutting speed with 32.16% and 27.98% respectively. While, gas pressure showed the most significant effect on kerf width having 41.99% followed by the cutting current with 27.51% and the least significant parameter was the cutting speed with 22.62%.

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