Engineering and Technology Journal
Journal homepage: engtechjournal.org

Optimization of Plasma Cutting Parameters on Dimensional Accuracy and Machining Time for Low Carbon Steel

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Submitted: 10/11/2019 Accepted: 10/01/2020 Published: 25/08/2020

K E Y W O R D S

Plasma arc cutting, dimensional accuracy, machining time, response surface methodology (RSM),

A B S T R A C T

This work aims to study the influence of plasma arc cutting parameters on dimensional accuracy and machining time for mild steel (1010) material with the thickness (4 mm). Selected three cutting parameters (arc current, cutting speed, and arc distance) or the experimental work. 12 tests have been performed at each test one parameter has been changed with four various levels and other parameters are constant. The influence of the cutting parameters on response results (dimensional accuracy and machining time) have been studied and analyzed by using response surface methodology (RSM) using the second-order model and main effect plot have been generated of each parameter on response results by using ANOVA depended on results of response surface analysis. The results of the response surface analysis showed that the important influencing parameters on dimensional accuracy were cutting speed and arc current as well as on deviation of dimensional accuracy, and the machining time is further affected with the current more than the cutting speed and the standoff distance. The outcomes of response surface analysis showed that the optimal setting of the cutting parameters to obtain at high dimensional accuracy were (arc current= 110 A, cutting speed = 4000 m/min, arc distance = 2mm) and to obtain on less machining time was (arc current= 110 A, cutting speed = 4000 m/min, arc distance = 5mm).

How to cite this article: Sami A. H., Vian N. N., "Optimization of plasma cutting parameters on dimensional accuracy and machining time for mild steel," Engineering and Technology Journal, Vol. 38, Part A, No. 08, pp. 1160-1168, 2020.
DOI: https://doi.org/10.30684/etj.v38i8A.1151

1. Introduction

The requirement of the market is to obtain high productivity, the best quality of the surface and machining complex shapes geometry, which leads to the exchange of traditional cutting processes with non-traditional cutting processes. The plasma arc cutting process is supposed one from the thermal and non-traditional cutting processes, which used thermal energy with high ionized gas to molten and cut products. The temperature of the gas passing through a small gap in the plasma cutting process is increased from (20000 C° to 30000 C°) and cutting velocity can approach the speed of sound. The atoms of the gas become ionized at maximum temperature (30000C°) and the gas in this step is called plasma. Because of the rising temperature and speed produced in plasma cutting process which leads to very rapidly melted and vaporized the material of the work part by persistent electrical arc passing through the nozzle have a small gap and created between the cathode (electrode) and the anode (work part) depended on the thickness and electrical features of conductive engineering materials [1,2,3,4]. The plasma machine systems can be divided into air plasma system when used only compressed air and by supplement water-cooled nozzle this system called shielded plasma. The current used in plasma machine have a range (20 - 1000) amperes to cutting the conductive materials have a thickness (5 mm to 160 mm) by using the gas such as (compressed air, nitrogen, oxygen, or argon- hydrogen) [1,4]. In the plasma arc cutting operation, the power required of the process must have low properties energy and high voltage. The energy densities that can be achieved to cutting parts in the plasma beam up to (2X106 W/cm2) and voltage required to keep the plasma constant is typically about (100 – 160) V. The voltage of open circuit required to create the electrical arc can be reached to 400V DC [1,4,5]. Plasma arc cutting process has significant advantages compared with other non-conventional cutting processes such as high cutting velocity and high accuracy of dimensions, moderate to the low cost of instruments, and various types of conductive metals with any thickness can be cut [4,6,7,8]. Plasma arc cutting machine can be controlled either manually or by CNC (computer numerical control) machine which gives more flexibility for designers and workers. Therefore, there is no need for high skilled workers compared with manually plasma arc cutting machines. Naik et al. [9] presented the effect of cutting parameter (voltage, the height of cut, and cutting speed) on the accuracy of dimensions of plasma cutting process for stainless steel plate 304L has a thickness of 10 mm used Taguchi experimental technique with L16 orthogonal matrix for measured the Linear dimension. selected three levels for each of the cutting parameters for experimental work. Evaluated the influence of each machining parameter performed by analysis of variance (ANOVA) for mathematical data and analysis of means (ANOM) for the plot. The results showed that the improved in linear dimension on the x-axis lead to an improved in machinability. Kenan M. et.al [6] proposed experimentally and analyzed the quality of the surface (kerfs width and bevel angle) of plasma cutting operation for stainless steel (316L) work piece have the various thickness (4, 8, 12) mm by using the grey relational method. used cutting factors (cutting speed, voltage, and pressure of gas) for experimental tests. used air as a gas of the cutting process, have less cost compare with used other gases. Estimated the effect of each process factor on the quality of the surface by using ANOVA. The outcomes showed that voltage was the important influencing factors on kerfs width compare with other cutting factors (pressure of gas and cutting speed). Whereas bevel angle, effected by cutting velocity compare with other cutting factors (voltage and pressure of gas. Ivan et al. [7] developed the artificial Neural Network (ANN) mathematical model for prediction of kerf width in the plasma arc machining process. analyzed influence the machining parameters such as the height of cut, cutting speed & current. Used the Taguchi method with matrix L18 (21x37) for the experimental design of Al-alloy (5083) with thickness 3 mm developed artificial neural network mathematical model depended on the experimental data. The artificial neural network approach was used for mathematical modeling and to identify process parameters ranges that lead to optimal kerf width values. According to the ANN model, the plots were generated that can be used to show process parameters influence and to identify the optimal cutting conditions which correspond to the minimal kerf width. Patel et al. [8] analyzed the effects factors of plasma arc cutting process for Al- alloy (6082) plate with a thickness (5) mm selected The machining factors with three levels for optimization were (current, cutting speed, pressure, and arc gap). The experiment tests were performed by the response surface method (RSM). The outcomes of operation were estimated and analyzed such as (top kerfs width, bottom kerfs width, rate of material removal, and bevel angle). The ANOVA outcomes showed that the most significant machining factors for Top & bottom kerfs width and the bevel angle was current with a contributing percentage (52.06%), (54.90%), and (44.36%) respectively. Many attempts of machining factors optimization on bevel angle and micro-hardness were performed during the plasma

arc machining process of mild steel (St37) plate using Taguchi experimental method. The selected cutting factors were (cutting speed, arc ampere, pierce height, and torch standoff distance) for experimental tests. The outcomes defined the current and the cutting velocity influenced on the bevel angle and the micro-hardness, respectively. The pierce height and the torch standoff distance influenced both the bevel angle and the material micro-harness [10].
This work presents a study of the influence of plasma arc cutting process parameters (arc current, cutting speed and arc distance) on dimensional accuracy and machining time for mild steel (1010) material with the thickness (4 mm), the various parameters affect have been analyzed by using response surface methodology (RSM).

2. Experimental Procedures

I. Materials

In this research mild (low carbon) steel (1010) plate used as a work piece have a dimension (230X90X4) mm have been prepared for the experimental work as shown in Figure 1. This alloy is used in engineering industries machines that lead to low cost, best mechanical strength, and used in daily life such as mounting plates, tools and die sets, machinery frames, special bolts. The chemical composition of this material given in Table 1. The machining process has been achieved by using a CNC plasma cutting machine kind (LGK-120IGBT). Compressed air is used as a cutting gas. Square blocks cut have a dimension of (24X24X4 mm) that has been cut from the original plate for all 12 tests. In all tests, the direction of the cut was clockwise.

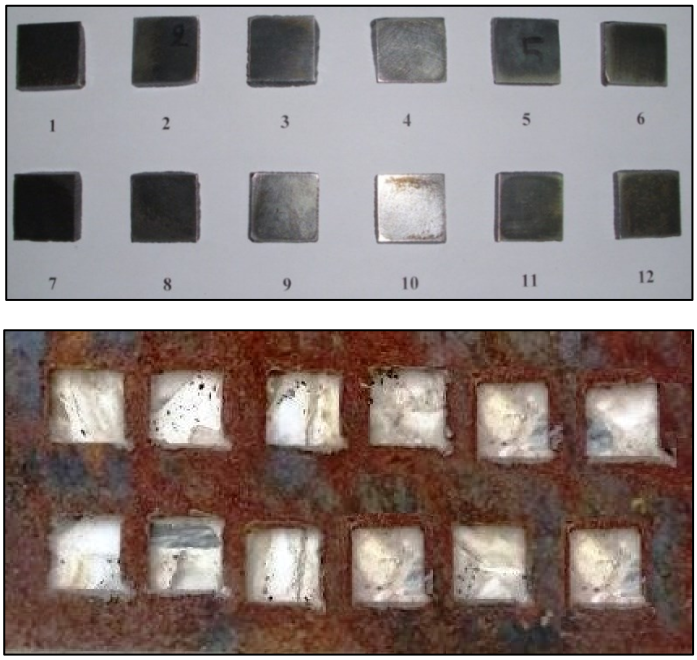

Figure 1: Work piece and scrap

Table1: Chemical composition of work piece

element	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Fe
weight%	0.124	0.033	0.44	0.0084	0.0032	0.0154	0.002	0.033	0.044	0.010	Bal.

II. Selection of Cutting Parameters

In order to know the effect of cutting factors on the operation performance. Response surface method has been used, using a second-order mathematical model. Three cutting factors have been selected (arc current, cutting speed, and arc distance) for the experimental tests. Run of the experiment tests by response surface method, in which changes have been performed in the cutting factors in order to know the reasons for changes in the outcomes response. 12 experimental tests have been achieved, each test has one-factor change with four various levels and other factors remained constant as shown in Table 2.

Table 2: Machine cutting factors considered in RSM.

arc current (ampere)	arc distance (mm)	Speed (m/min)
80	3	3000
90	3	3000
100	3	3000
110	3	3000
90	3	1000
90	3	2000
90	3	3000
90	3	4000
90	2	3000
90	3	3000
90	4	3000
90	5	3000

III. Measurement and Instrument

A digital caliper with an accuracy of (0.001) has been used to measure the linear dimensions of the finished part in Figure 2, in order to measure the accuracy of the dimensions. The dimension measurements have been achieved by taking three measurements along (x)-axes and three measurements along (y)-axes on the top surface and then the average of six measurements of the cut part as shown in Figure 3 have been estimated. The deviations (the difference between the maximum and minimum value of six measurements) of six measurements have been measured for each of the cut parts. The results which are obtained through measurements are summarized in Table 3.

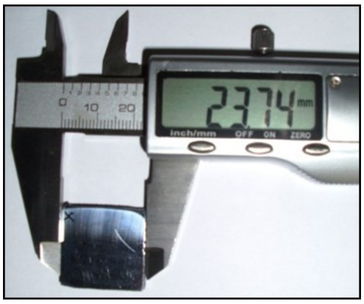

Figure 2: Digital caliper with work piece

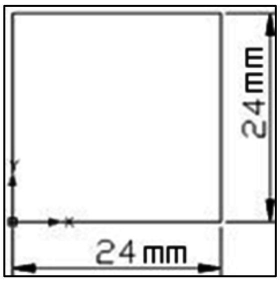

Figure 3: Work piece with direction of measurement

2. Results and Discussion

The runs of experimental outcomes were achieved by response surface method for know the response of dimensional accuracy and machining time with the influence of cutting variables. The outcomes have been summarized in Table 3.

Table 3: The outcomes of experimental tests achieved by response surface methodology

Test NO.	arc current	arc distance	speed	top dimension average (mm)	deviation (max value-min value)	time (sec)
1	80	3	3000	22.89	0.44	6.37
2	90	3	3000	23.41	0.51	4.36
3	100	3	3000	23.58	0.52	3.08
4	110	3	3000	23.74	0.31	2.28
5	90	3	1000	23.18	0.72	6
6	90	3	2000	23.27	0.64	4.88
7	90	3	3000	23.42	0.51	4.36
8	90	3	4000	23.69	0.23	3.73
9	90	2	3000	23.64	0.77	5.88
10	90	3	3000	23.43	0.54	4.36
11	90	4	3000	23.39	0.21	3.68
12	90	5	3000	22.93	0.36	2.83

I. Response Surface Methodology Model Summary

In the outcomes, the statistics used as model summary to estimate how well the mathematical model fits the experimental data [11-13] shown in the Tables 6,7,8. The symbols of cutting factors used in the response surface method and the symbols of output found in the response surface model are shown in tables 4 and 5.

Table 4: The symbols of cutting factors used in response surface methodology

parameter	current	arc distance	speed
symbol	c	a	s

Table 5: The symbols of output found in response surface model .

symbol	meaning	description
S and R	adjusted R and predicted R	Used to measures of how well the model fits the data compare with experimental data
DF	degrees of freedom from each factor	If a factor has three levels, the degrees of freedom is 2 (n-1)
SS	sum of squares	The sum of squares between groups (factor) and the sum of squares within groups (error)
MS	mean squares	can found by dividing the sum of squares by the degrees of freedom
P	Probability	use to determine whether a factor is significant
F	Fisher ratio (variance ratio)	calculate by dividing the factor MS by the MS error

I.1.Model Summary for Response Top Dimension

From the statistical model outline as shown in the Table 6 (response top dimension) can be concluded that [11,12]:

1. The R2 value was (94.41 %) which lead to that the response statistical model fits the data experimental tests adequately.
2. The R2 (adj) value was (87.69 %) which lead to that fitness between the experimental data and the created square (second-order) statistical model.
3. The R2 predicted value was (0%) supposed that the statistical model is over fitted, which helps to reduce the statistical model.
4. The p-values were (0.002) in linear and (0.027) in square statistical model less than (0.05) of current which indicated that the current more important factor on the dimensional accuracy of top surface compares with other factors (arc distance, cutting speed).

Table 6: Model summary for response top dimension

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0.7864	0.131	14.06	0.005
Linear	3	0.7458	0.2486	26.67	0.002
c	1	0.3545	0.3545	38.03	0.002
a	1	0.2169	0.2169	23.28	0.005
s	1	0.1523	0.1523	16.34	0.010
Square	3	0.1187	0.0395	4.25	0.077
c*c	1	0.0893	0.0893	9.59	0.027
a*a	1	0.0035	0.0035	0.38	0.566
s*s	1	0.0101	0.0101	1.09	0.345
Error	5	0.0466	0.0093		
Lack-of-Fit	3	0.0464	0.0154	154.69	0.006
Pure Error	2	0.0002	0.0001		
Total	11	0.833			
Model Summary					
S		R-sq	R-sq(adj)	R-sq(pred)	
0.0965482		94.41%	87.69%	0.00%	

I.2.Model Summary for Response Deviation in Dimension

From the statistical model outline as shown in the Table 7 below (response deviation in dimension) can be concluded that [11,12]:

1. The R2 value was (89.29%) which lead to that the response statistical model fits fit the data experimental tests adequately.
2. The R2 (adj) value was (76.44 %) which lead to that fitness between the experimental data and the created square (second-order) statistical model.
3. The R2 predicted value was (0%) supposed that the statistical model is over fitted, which helps to reduce the statistical model.
4. The P-values were (0.008) and (0.010) in linear statistical model less than (0.05) of arc distance and cutting speed which leads to the arc distance and cutting speed important factor on deviation in the dimension compares with arc current.
5. The P-value was greater than (0.1) for all cutting factors in the square (second-order) statistical model which indicated that all cutting factors not important factors on deviation in dimension.

Table 7: Model Summary for Response Deviation in Dimension

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0.3348	0.0558	6.95	0.025
Linear	3	0.2946	0.0982	12.23	0.010
c	1	0.0064	0.0064	0.80	0.412
a	1	0.1492	0.1492	18.58	0.008
s	1	0.1298	0.1298	16.16	0.010
Square	3	0.0829	0.0276	3.44	0.108
c*c	1	0.0219	0.0219	2.73	0.159
a*a	1	0.0252	0.0252	3.15	0.136
s*s	1	0.0203	0.0203	2.53	0.172
Error	5	0.0401	0.0080		
Lack-of-Fit	3	0.0323	0.0107	2.77	0.277
Pure Error	2	0.0078	0.0039		
Total	11	0.3750			
Model Summary					
S		R-sq	R-sq(adj)	R-sq(pred)	
0.0896295		89.29%	76.44%	0.00%	

I.3.Model Summary for Response Machining Time

From the statistical model outline as shown in the Table 8 below (response top dimension) can be concluded that [11,12]:

1. The R2 value was (99.24 %) which lead to that the response statistical model fits the data experimental tests adequately.
2. The R2 (adj) value was (98.33 %) and the R2 predicted value was (75.97 %) which indicates the good agreement of the experimental data with predicted data to the generated square (second-order) model and the statistical model is appropriate for response and analysis machining time
3. The p-values were (0.00) in a linear statistical model less than (0.05) of all cutting factors which indicated that all cutting factors are important on machining time.
4. The p-values were (0.008) and (0.010) in square statistical model less than (0.05) of arc current and arc distance which indicated that the arc current and arc distance important factors on machining time compare with cutting velocity.

Table 8: Model summary for response machining time

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	18.3137	3.05228	108.92	0.000
Linear	3	17.4772	5.82574	207.88	0.000
c	1	9.7462	9.74618	347.78	0.000
a	1	4.9099	4.90994	175.20	0.000
s	1	2.6728	2.67282	95.38	0.000
Square	3	0.6966	0.23221	8.29	0.022
c*c	1	0.5411	0.54107	19.31	0.007
a*a	1	0.2876	0.28762	10.26	0.024
s*s	1	0.0218	0.02177	0.78	0.418
Error	5	0.1401	0.02802		
Lack-of-Fit	3	0.1401	0.04671		
Pure Error	2	0.0000	0.00000		
Total	11	18.4538			
Model Summary					
S		R-sq	R-sq(adj)	R-sq(pred)	
0.167404		99.24%	98.33%	75.97%	

II. Regression Analysis in Response Surface Methodology

Regression analysis is a statistical forecasted used to gauge the relationship between factors of inputs (independent variable) in the original units of the data and factors of outputs (dependent variable) second-order regression statistical model is created because the first order statistical model often give a lack to fit data [11,12].

The regression equation for top dimension

$TOP\ DIM = 9.94 + 0.2629\, c - 0.029\, a - 0.000041\, s - 0.001248\, c\times c - 0.0248\, a\times a + 0.000000\, s\times s$

The regression equation for Deviation

$DIV = -3.33 + 0.1140\, c - 0.632\, a + 0.000142\, s - 0.000618\, c\times c + 0.0664\, a\times a - 0.000000\, s\times s$

The regression equation for machining time

$TIME = 52.26 - 0.719\, c - 2.528\, a - 0.001017\, s + 0.003070\, c\times c + 0.2239\, a\times a + 0.000000\, s\times s$

4. Main Effect Plots

The objective of the variance analysis (ANOVA) to obtain the effect of the selected factors on the accuracy of dimensions and machining time. ANOVA has been supported to compare the factors within data of experimental work as shown in Table 3.

From Figure 4, it can be deduced that the accuracy of dimensions for top surface increase with the increase of cutting speed and current which leads to more heat created at the top surface which is influencing the surface appearance as well as the dimension of the surface, while the accuracy of dimensions' decreases with the increase of stand-off distance.

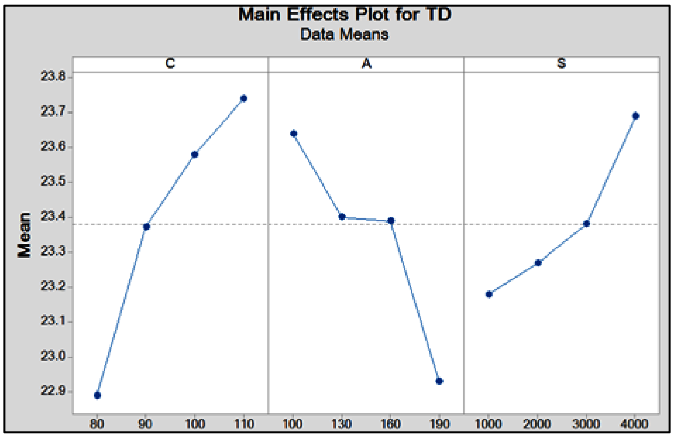

Figure 4: Main effect plot for cutting factors on top dimensions

From Figure 5, it can be noticed that deviation decrease with increase the current and the standoff distance for the first three experiments but at the last experiments the deviation increase with the increase in the current and standoff distance which means that the current and standoff distance at high values gives more deviation and the deviation decreases with the increase in the cutting speed.

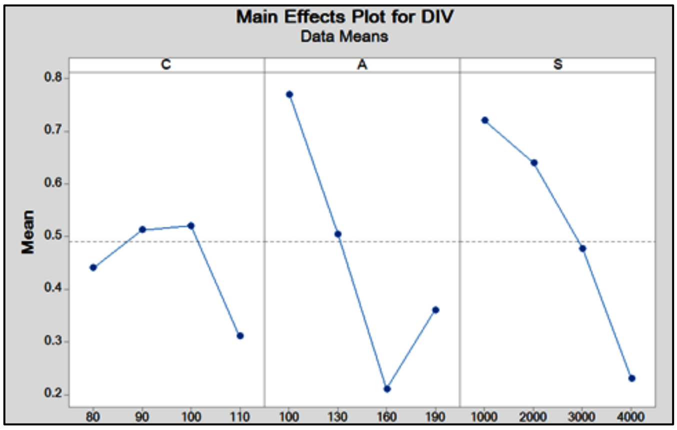

Figure 5: Main effect plot for cutting factors on deviation in accuracy of measure dimensions.

Figure 6 shows that the machining time decrease with an increase in current the scientific reason behind that is when the amount of current increases, the heat generated in the cutting zone risen which in turn leads to more material removes in less time. The machining time decreases when the cutting speed increases because the increase in cutting speed leads to supplementary heat generation as well as the standoff distance. It is obvious from the above scheme that the machining time is further affected by the current more than the cutting speed and the standoff distance.

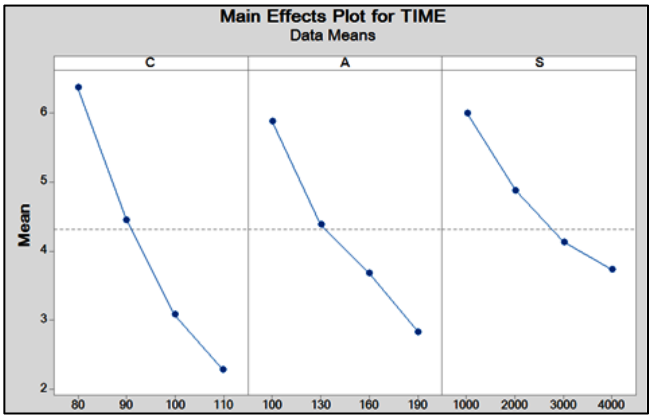

Figure 6: Main effect plot for cutting factors on machining time.

5. Conclusions

The aim of this work is to optimize plasma cutting parameters and have the best dimensional accuracy and machining time. From the experimental results and analysis of results obtained the following points can be concluded:

1. The dimensional accuracy of top surface increase with the increase of cutting speed and arc current which leads to good surface quality, as well as decreases with the increase of arc distance.
2. Deviation decrease with increase arc current and the arc distance which means that the arc current and the arc distance at high values give more deviation, and the deviation decreases with increase the cutting speed.
3. The machining time decrease with an increase in arc current, the machining time also decreases when the cutting speed and arc distance increases which in turn leads to maximum productivity (maximum material removal rate) in less time.
4. The machining time and dimensional accuracy are further affected by the arc current more than the cutting speed and the arc distance.
5. The arc distance was the major effect factor on the deviation of dimensional accuracy.

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