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A parameter design of CNC plasma-arc cutting of carbon steel plates using robust design

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Abstract: An optimisation of the cutting parameters during CNC plasma-arc cutting of St37 mild steel plates is attempted using robust design. The process parameters tested were plate thickness, cutting speed, arc ampere, arc voltage, air pressure, pierce height, and torch standoff distance. An orthogonal matrix experiment [L_{18} ($2^1 \times 3^7$)] was conducted and the right bevel angle was measured and optimised according to the process parameters using an analysis of means and an analysis of variances. The results show that the arc ampere has an effect mainly on the bevel angle (50.89%), while the plate thickness and torch standoff distance also have an influence of 6.22 and 15.9% respectively. The other parameters have an F factor smaller than one, and thus their variations do not significantly affect the bevel angle in the experimental region. Finally, an additive model was applied on the experimental results to predict the optimum combination and was compared with actual values.

Keywords: plasma-arc cutting; PAC; carbon steel plates; robust design.

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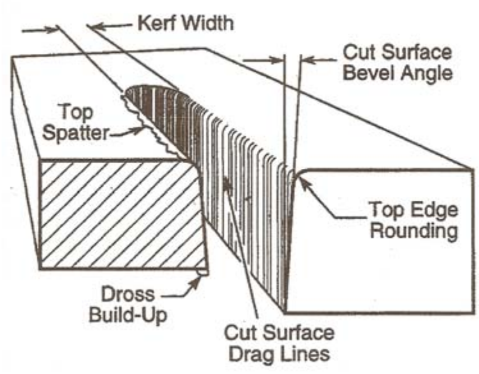
1 Introduction

Plasma-arc cutting (PAC) is used when low volume pressed metal (carbon steel, stainless-steel, aluminium, cast iron and non-ferrous metals) panels and tubes are cut, trimmed and pierced rapidly (Kalpakjian, 1995). Other thermal processes which are antagonistic with PAC are the laser beam machining process (LMP) and flame cutting. The choice of the most suitable of these processes for industrial applications depends on several factors such as type of material, layer thickness, cutting speed and quality indicators (Figure 1) of each process as well as cost. PAC can be used in cutting of metal plates from approximately 5 to 40 mm thickness.

Figure 1 Quality indicators of PAC



Experimental multi-parameter optimisation of the PAC process according to quality indicators such as kerf characteristics, dimensional accuracy and quality of cut surface have been studied by several researchers in several materials and experimental regions (Gariboldi and Previtali, 2005; Gullu and Atici, 2006; Zhou et al., 2008; Bini et al., 2008; Narimanyan, 2009; Chen et al., 2009; Vejandla, 2009; Asiabanpour et al. 2009).

A research work (Gariboldi and Previtali, 2005) investigated the quality of cuts performed on titanium sheets of 5 mm thickness. They tried several feed rates and used oxygen or nitrogen as cutting gases.

Furthermore, an investigation of the PAC parameters on the structure variation and hardness of the heat affected area of AISI and St52 steels was carried out by other researchers (Gullu and Atici, 2006).

In addition, the influence of nozzle length, arc current, and mass flow rate on plasma cutting arc was investigated in research work (Zhou et al., 2008).

In research work (Bini et al., 2008) a design of experiments approach was used to experimentally investigate the influence of cutting parameters on kerf characteristics. They found that on cutting of 15 mm mild steel plates by high tolerance PAC process, the most influencing parameters on kerf characteristics are the cutting speed and the arc voltage.

In research work (Narimanyan, 2009) the cut front during plasma cutting was modelled using unilateral conditions in a finite element modelling approach.

An industrial case study (Chen et al., 2009) investigated the influence of the cutting process parameters on roundness of holes made by an aging plasma-cutting machine using the design of experiments approach.

Finally, in MSc thesis (Vejandla, 2009; Asiabanpour et al. 2009) the influence of the process parameters of a CNC PAC machine was investigated on cutting of mild steel, and regressions models were extracted for the prediction of several quality indicators.

The current research work investigates the influence of plasma-arc cut process parameters on right side bevel angle of St37 mild steel cut surface (Figure 3). A multi-parameter optimisation was carried out using the robust design (Phadke, 1989; Kwak, 2005; Kechagias, 2007a, 2007b; Kechagias and Iakovakis, 2009; Kechagias et al., 2009) and the L18 orthogonal matrix experiment.

The selection of quality characteristics, material, plate thickness and other process parameter levels and experimental limits was decided after real practice and market research of what the Greek industry of metal cutting requires.

2 Experimental setup

In the experimental tests, St37 carbon steel (mild steel) which is widely used in industrial applications has been utilised. The CNC PAC machine uses a Thermal Dynamics® torch; PCH/M-120 type, and air gas.

Two plates of 6.5 mm, and 10 mm thickness were used for the matrix experiment (Figure 2).

Figure 2 Experimental plates of St37 (see online version for colours)

A seven parameter design was performed as shown in Table 1. The standard $L_{18}(2^1 \times 3^7)$ orthogonal matrix experiment was used (Table 2). Columns 1, 2, 3, 4, 5, 6 and 7 are assigned to plate thickness (A, mm), cutting speed (B, m/min), arc ampere (C, Amp), arc voltage (D, Volt), air pressure (E, bar), pierce height (F, mm), and torch standoff distance (G, mm), respectively.

Table 1 Parameter design

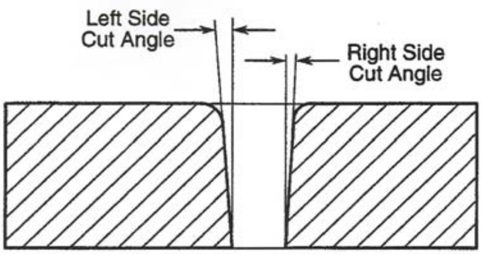
No	*Process parameters*		*Units*	*Level 1*	*Level 2*	*Level 3*
1	A	Plate thickness	mm	6.5	10	-
2	B	Cutting speed	m/min	1	2.5	4
3	C	Arc ampere	amp	30	70	110
4	D	Arc voltage	volt	100	130	160
5	E	Air pressure	bar	4.5	4.65	4.8
6	F	Pierce height	mm	3.3	4.8	6.4
7	G	Torch standoff distance	mm	3.3	6.4	9.5

Table 2 Orthogonal array L_{18} $(2^1 \times 3^7)$

Exp. no	*Column*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

A 20 mm diameter hole of was cut in each of the 18 combinations as indicated in the orthogonal matrix experiment. The direction of the cut was counter clock wise (CCW) in order to measure the right side cut angle (right bevel angle), Figure 3.

Figure 3 Section of PAC



Multi-parameter optimisation of the process according other quality indicators (Figure 1) such as kerf width, cut surface hardness, top edge rounding, dimensional accuracy, accumulation of metal underneath the part (dross build up), and surface quality parameters will be studied and analysed in future work.

The right bevel angle was measured as follows:

$$a = \text{atan}[(D_{up} - D_{down})/(2*\text{plate thickness})] \quad (1)$$

where a is the right bevel angle, D_{up} the hole diameter at the top, and D_{down} the hole diameter at the bottom.

3 Experimental results and analysis

The Taguchi design method is a simple and robust technique for optimising the process parameters. In this method, the main parameters, which are assumed to have an influence on process results, are located at different rows in a designed orthogonal array. With such an arrangement randomised experiments can be conducted. In general, the signal to noise (S/N) ratio (n, dB) represents the quality characteristics of the data observed in the Taguchi design of experiments.

In the case of the right bevel angle, lower values are desirable. These S/N ratios in the Taguchi method are known as the smaller-the-better characteristics and are defined as follows:

$$\eta = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \quad (2)$$

where y_i is the observed data at the ith trial and k is the number of trials. From the S/N ratio, the effective parameters having an influence on process results can be seen and the optimal sets of process parameters can be determined.

Based on robust design, the standard orthogonal array $L_{18}(2^1 \times 3^7)$ has been selected in order to perform the matrix experiment (Table 3). The plate thickness was selected to have two values, while the others were selected to have tree values each (Table 1). According to the $L_{18}(2^1 \times 3^7)$ orthogonal array 18 experiments were performed with each experiment producing a hole which was tested for right bevel angle. Then each performance measurement η_i was calculated according to the formula:

$$\eta_i = -10 \log_{10}(a_i) \quad (3)$$

Table 3 Matrix experiment

No of exp.	*Process parameters*								*Performance measures*			
	A	*B*	*C*	*D*	*E*	*F*	*G*	-	D_{up} *(mm)*	D_{down} *(mm)*	*a* *(°)*	η_a *(dB)*
1	6.5	1	30	100	4.5	3.3	3.3	1	20.05	18.17	8.23	–9.15
2	6.5	1	70	130	4.65	4.8	6.4	2	20.73	19.37	5.97	–7.76
3	6.5	1	110	160	4.8	6.4	9.5	3	21.61	20.82	3.48	–5.41
4	6.5	2.5	30	100	4.65	4.8	9.5	3	20.71	18.63	9.09	–9.59
5	6.5	2.5	70	130	4.8	6.4	3.3	1	19.85	19.12	3.21	–5.07
6	6.5	2.5	110	160	4.5	3.3	6.4	2	21.16	20.98	0.79	1.01
7	6.5	4	30	130	4.5	6.4	6.4	3	20.83	19.55	5.62	–7.50
8	6.5	4	70	160	4.65	3.3	9.5	1	21.36	20.44	4.05	–6.07
9	6.5	4	110	100	4.8	4.8	3.3	2	20.53	20.51	0.09	10.55
10	10	1	30	160	4.8	4.8	6.4	1	20.39	17.33	8.70	–9.39
11	10	1	70	100	4.5	6.4	9.5	2	21.07	18.74	6.65	–8.22
12	10	1	110	130	4.65	3.3	3.3	3	20.76	20.52	0.69	1.63
13	10	2.5	30	130	4.8	3.3	9.5	2	21.4	17.29	11.61	–10.65
14	10	2.5	70	160	4.5	4.8	3.3	3	20.39	18.69	4.86	–6.86
15	10	2.5	110	100	4.65	6.4	6.4	1	21.64	20.51	3.23	–5.10
16	10	4	30	160	4.65	6.4	3.3	2	19.18	16.64	7.24	–8.60
17	10	4	70	100	4.8	3.3	6.4	3	20.78	18.68	5.99	–7.78
18	10	4	110	130	4.5	4.8	9.5	1	21.96	20.34	4.63	–6.66
Mean											5.23	–5.59

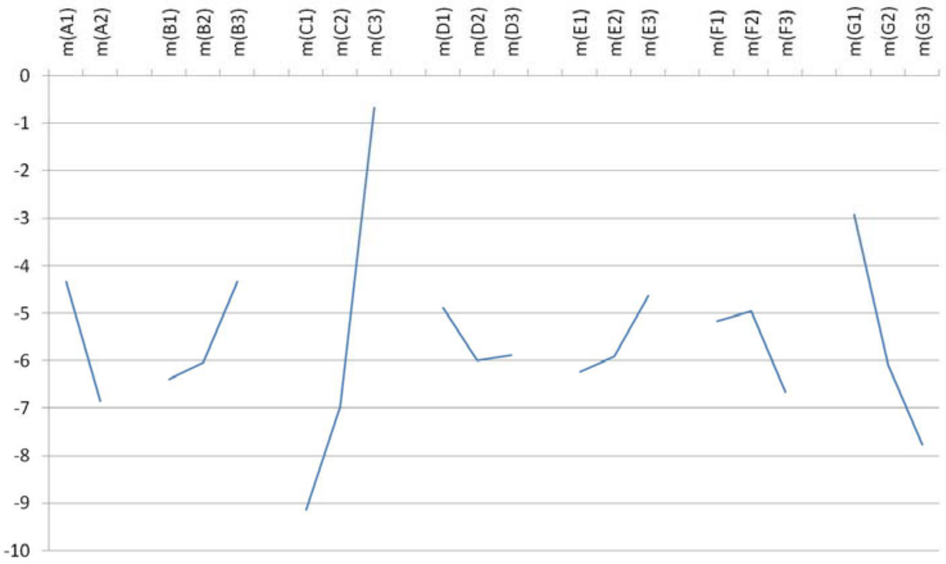
For each of the seven process parameters an average m_i for every level was calculated (Table 4).

Table 4 Mean parameter values

Mean parameter values		*Level 1*	*Level 2*	*Level 3*
m_{Ai}	A	–4.33	–6.85	-
m_{Bj}	B	–6.39	–6.04	–4.34
m_{Ck}	C	–9.15	–6.96	–0.66
m_{Dl}	D	–4.88	–6.00	–5.89
m_{Em}	E	–6.23	–5.91	–4.63
m_{Fn}	F	–5.17	–4.95	–6.65
m_{Go}	G	–2.92	–6.09	–7.77

Based on the average values, an analysis of means (ANOM) diagram (Figure 4) was constructed indicating the impact of each factor level on the performance η_a of the parts produced. Thus, based on the ANOM, one can derive the optimum combination of process variables, with respect to performance. The optimum level for a factor is the level that gives the maximum value of the η in the experimental region.

Figure 4 ANOM diagram (see online version for colours)



According to the ANOM diagram the arc ampere and the torch standoff distance during cutting affect the right bevel angle mostly. The optimum combination of the parameter levels according to the objective function η is shown in Table 5.

Table 5 Optimum combination of parameter levels

No		*Process parameters*	*Units*	*Level*
1	A	Plate thickness	mm	6.5
2	B	Cutting speed	m/min	4
3	C	Arc ampere	amp	110
4	D	Arc voltage	volt	100
5	E	Air pressure	bar	4.8
6	F	Pierce height	mm	4.8
7	C	Torch standoff distance	mm	3.3

According to robust design, the interaction between two or more parameters can be classified as:

1 no interaction

2 synergistic interaction

3 antisynergistic interaction.

Figure 5 shows the interaction type between the arc ampere and the standoff distance. It can be seen that when the standoff distance is decreased from 9.5 to 6.4 or 3.3 mm the corresponding change in η_{Ra} is increased in relation to the level of arc ampere parameter.

Thus, it can be concluded that there is a ‘synergistic interaction’ between the two parameters.

On the other hand the conflicting lines in Figure 6 show an ‘antisynergistic’ interaction between arc ampere and plate thickness process parameters.

Figure 5 Interaction chart between arc ampere and standoff distance (see online version for colours)

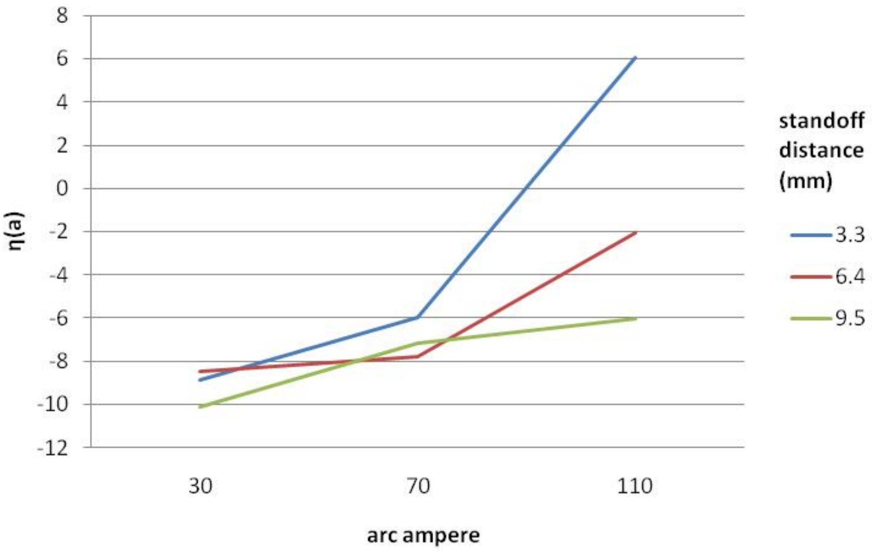
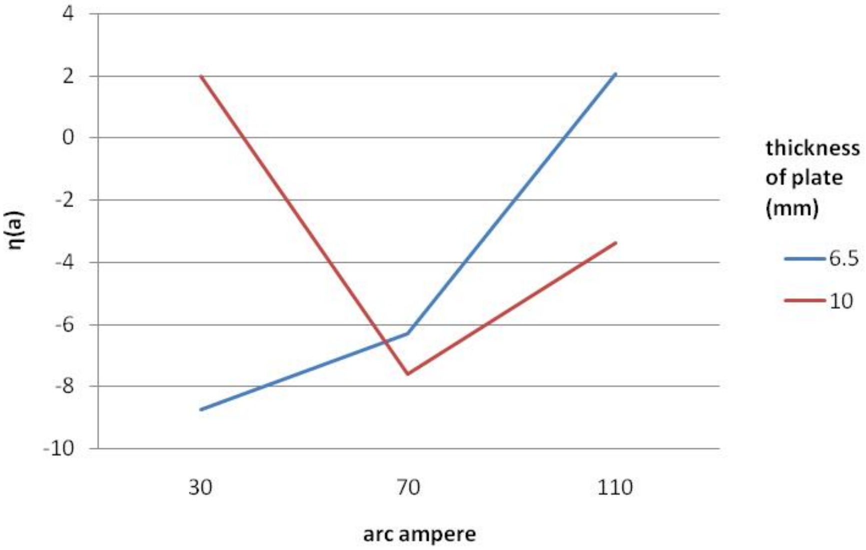


Figure 6 Interaction chart between arc ampere and plate thickness (see online version for colours)



Robust design performs an analysis of variables (ANOVA) of the experimental results in order to evaluate the relative importance of the process parameters and error variances. The ANOVA analysis results can be seen in Table 6.

Table 6 ANOVA analysis

		Degrees of freedom	*Sum of squares*	*Mean squares*	*F*	*%*
A	Plate thickness	1	28.45	28.45	2.77	6.22%
B	Cutting speed	2	14.38	7.19	0.70	3.14%
C	Arc ampere	2	232.76	116.38	11.31	50.89%
D	Arc voltage	2	4.56	2.28	0.22	1.00%
E	Air pressure	2	8.68	4.34	0.42	1.90%
F	Pierce height	2	10.24	5.12	0.50	2.24%
G	Torch standoff distance	2	72.75	36.37	3.54	15.90%
Total		17	457.43			
Pulled error		12	123.46	10.29		

Figure 7 Factor percentage influence (see online version for colours)

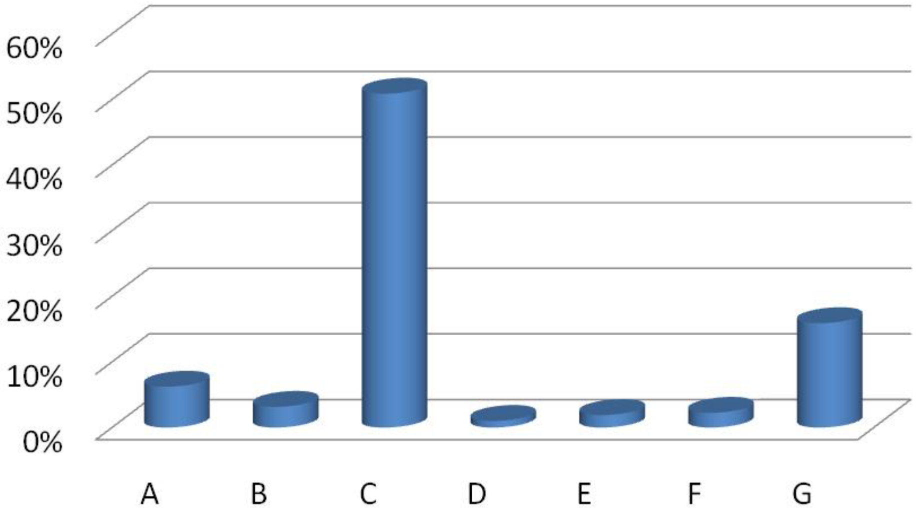


Figure 7 shows the influence of each factor on the right bevel angle. According to the ANOVA analysis the plate thickness, the arc ampere and the torch standoff distance during cutting affect the right bevel angle by 6.22, 50.89 and 15.90% respectively. The effect of the other process parameters can be attributed to error as they have a negligible impact on the quality indicator inside the experimental region.

The variance of the effect of each factor level for this case is (Phadke, 1989):

$$\frac{1}{3}\sigma_e = \frac{1}{3}(10.29) = 3.429 \tag{4}$$

thus, the width of the two standard deviation confidence intervals, which is approximately 95% of the confidence interval for each estimated effect, is

$$e = \pm 2\sqrt{3.429} = \pm 3.703 \tag{5}$$

In order to establish a relationship between the performance η and the process parameters, one can derive the additive model of the form

$$\eta = m + (m_{Ai} - m) + (m_{Ck} - m) + (m_{Go} - m) \pm e \tag{6}$$

where η is the performance measure, m is the overall mean of all the performance measures (Table 3), and m_{Ai}, m_{Ck}, and m_{Go} are the means of each parameter level (Table 4).

For example the prediction of the performance of the best combination (A1, C3, G1) is

$$\begin{aligned}\eta_{131} &= m + (m_{A1} - m) + (m_{C3} - m) \\ &\quad + (m_{G1} - m) \pm e\end{aligned} \tag{7}$$

or

$$\begin{aligned}\eta_{131} &= -5.59 + (-4.33 + 5.59) + \\ &\quad (-0.66 + 5.59) + \\ &\quad (-2.92 + 5.59) \pm 3.703\end{aligned} \tag{8}$$

or

$$\eta_{131} = 3.27 \pm 3.703 \tag{9}$$

An evaluation experiment was performed and the η_{131} was found to be 4.05; a value which is acceptable as it is inside the above confidence intervals.

4 Conclusions

The right bevel angle has been selected as the quality indicator for PAC process multi-parameter optimisation using robust design. A right bevel angle near zero means less post processing of the part. The experimental design showed that the arc ampere is the most important parameter that affects the right bevel angle by 50.89%. The torch standoff distance affects the right bevel angle by 15.9% and the plate thickness by about 6.22%. All the other process parameters used in the orthogonal experiment had a negligible effect on the right bevel angle within its experimental limits. The experimental limits were designed in order for all the combinations suggested in the orthogonal matrix to be able to be conducted. This means that if a combination could not be conducted the orthogonality would be lost and the conclusions would be unbalanced. Finally, an additive model was applied on the experimental results and a verification experiment, using the optimum combination of the parameter values, was carried out in order to compare the actual and the predicted values. The result is within the two sigma confidence intervals proposed by the methodology.

Multi-parameter optimisation of the process according to other quality indicators such as kerf width, cut surface hardness, top edge rounding, dimensional accuracy, accumulation of metal underneath the part and surface quality parameters will be studied and analysed in future work.

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