MULTI-RESPONSE OPTIMIZATION OF PLASMA CUTTING PARAMETERS USING GREY RELATIONAL ANALYSIS

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Abstract

In this paper was performed the optimization of the parameter of the plasma cutting process using Grey relational analysis. Design of experiments were carried out based on Taguchi L9 orthogonal array. Stainless steel X5CrNi18-10 plates with thickness of 5 mm were cut using different cutting speed and plasma gas pressure, while other process parameters were constant. The quality of the cut has been monitored by measuring surface roughness parameter R_z , cut perpendicularity and kerf width. Effect of each process parameter on quality characteristics of cut was shown. Optimal cutting parameters has been obtained by Grey relational analysis (GRA) method.

Keywords: plasma cutting; optimization; Grey relational analysis; Taguchi method; stainless steel

1. Introduction

Plasma arc cutting technology is one in which nitrogen, oxygen and compressed air are used to generate a plasma jet and then different type of materials such as nonferrous metal, stainless steel and others materials can be cut. During the plasma cutting process a source of heat is an electric arc generated by a plasma torch. The focus of manufacturers using plasma cutting process is optimization of productivity and the required quality of products made by plasma cutting. Both of these aspects are dependent on the appropriate choice of the process parameters. Plasma arc current, type gas, plasma gas pressure (plasma gas mass flow rate), cutting speed are parameters which have important effect on the quality characteristics. The effect of process parameters on the quality of the high tolerance plasma arc cutting of a 5 mm commercially pure titanium sheet was investigated in [1]. Authors concluded that the quality characteristics of the cutting edge of high tolerance plasma arc cutting of commercially pure titanium from a geometrical point of view need to be integrated with the considerations on the functional requirements for the cutting edge and on economical considerations that are partially correlated to microstructural modifications occurred at the cutting edge. A high tolerance plasma arc cutting system was used to cut plates of a 15 mm thick mild steel [2] and the arc voltage and cutting speed, plasma gas flow rate, shield gas flow rate and shield gas mixture are included in the analysis and their effects on kerf position and shape are evaluated.

It was shown that very good quality can be achieved for all the sides by varying the cutting speed and the arc voltage only. The effect of cutting speed and plasma gas pressure in plasma cutting of a 5 mm thick low alloy steel was analysed in [3]. It was shown that good quality cuts can be produced at the cutting speed from 400 to 700 mm/min and at the plasma gas pressure from 4 to 5 bar. Numerical method [4] and [5], genetic algorithms [6], statistical techniques [7] are common for the machining processes models. A new control strategy for plasma arc cutting was developed by [8] and this algorithm reduced the complexity of the nonlinear system modelling and achieved a real-time and online control for the cutting process by combining the advantages of fuzzy control and PID neural network control.

The regression analysis was used in [9] for the development of empirical models able to describe the effect of the process parameters on the cut quality in plasma arc cutting of a 15 mm thick mild steel sheets. It was found that the surface roughness and the kerf taper angle are mainly affected by the cutting height, whereas the heat affected zone is mainly influenced by the cutting current.

Investigation on the optimization and the effect of process parameters on material removal rate and surface roughness parameters during plasma arc cutting of EN31 steel using Taguchi method with grey relational analysis was presented in [10]. Also, analysis of variance was performed to get the contribution of each process parameters on the performance characteristics and it was observed that gas pressure is significant process parameters that affects the response.

The aim of this paper are to determine the effect and optimization of process parameters (cutting speed and plasma gas pressure) on surface roughness, kerf width and cut perpendicularity in plasma arc cutting of stainless steel a 5 mm thick using Grey relational analysis coupled with Taguchi method.

2. Experimental procedure

2.1. Test material, plasma cutting system and measuring equipment

The test material used in this experiment are X5CrNi18-10 steel plates. This steel belongs to austenitic stainless steel group. The chemical composition and mechanical properties of this steel are given in Tables 1 and 2.

Steel name	Steel number	Chemical composition (percentages by mass)							
		C	Si	Mn	P max.	S	N	Cr	Ni
X5CrNi18-10	1.4301	≤0,07	≤1,00	≤2,00	0,045	≤0,030	0,12-0,22	17-19,5	8,5-11,5

Table 1. Chemical composition of X5CrNi18-10 steel

Steel name	Steel number	Maximum hardness HB	Minimum 0,2 % proof strength, $R_{p0,2}$ N/mm ²	Tensile strength, R_m N/mm ²
X5CrNi18-10	1.4301	215	190	500-700

Table 2. Mechanical properties of X5CrNi18-10 steel

Cutting of test samples was performed using the *HiFocus 280i neo* plasma device. HiFocus technology is based on the plasma cutting principle with narrowed and stabilized plasma arc. Narrowing and stabilizing the plasma arc is achieved by using a smaller diameter nozzle, increased plasma gas rotation, and the additional application of the rotary gas to the plasma arc through a non-potential coaxial nozzle.

Measurement of surface roughness was performed on the *Mitutoyo SJ-210* measuring device. The surface roughness parameter R_z was measured at five different places along the cut edge. The *Mitutoyo TM-505* microscope was used to measure the cut perpendicularity and kerf width, which were measured at 9 different places along the edge of the cut.

2.2. Design of experiments

In this paper, a full experiment plan was used. Cutting speed and plasma gas pressure are varied for this experiment. Other process parameters were constant. A total of 9 samples were sampled for each combination of cutting speed and plasma gas pressure (Fig. 1).

Fig. 1. Test samples

In this experiment, there are two cutting parameters at three levels each. The cutting parameters levels are shown in the Table 3. Other constant parameters like current, voltage, nozzle distance from workpiece, types of plasma and secondary gas are shown in the Table 4.

Simbol	Cutting parameter	Level		
		1	2	3
A	Cutting speed V , mm/min	2000	2500	3000
B	Plasma gas pressure p , bar	6	8	10

Table 3. Cutting parameters and their levels

Constant parameter	Value
Current	60 A
Voltage	140 V
Nozzle distance	4 mm
Material thickness	5 mm
Plasma gas	N_2/H_2
Secondary gas	N_2

Table 4. Constant cutting parameters

The experimental layout for Taguchi L9 (3^2) orthogonal array is shown in Table 5.

Exp. No.	A Cutting speed	B Plasma gas pressure
1.	1	1
2.	1	2
3.	1	3
4.	2	1
5.	2	2
6.	2	3
7.	3	1
8.	3	2
9.	3	3

Table 5. Ortogonal array L9 (3^2) of the experimental run

3. Results and discussions

The aim of this paper is to determine the optimal plasma cutting parameters for minimizing surface roughness, kerf width and cut perpendicularity. The mean values of the surface roughness parameter R_z , kerf width and cut perpendicularity are given in Table 6.

Exp. No.	A Cutting speed V , mm/min	B Plasma gas pressure p , bar	Mean height of the profile R_z , μm	Cut perpendicularity u , μm	Kerf width a , μm
1.	2000	6	15,996	615,11	1991,1
2.	2000	8	13,756	514,05	2055,5
3.	2000	10	9,861	527,81	1971,4
4.	2500	6	8,192	424,82	1934,2
5.	2500	8	10,572	411,00	1990,7
6.	2500	10	11,851	421,59	1954,4
7.	3000	6	9,365	812,74	1871,4
8.	3000	8	10,272	426,77	1834,1
9.	3000	10	11,022	503,23	1962,8

Table 6. Experimental results

3.1 Effect of input parameters on the analyzed quality characteristics

In plasma cutting of termally cut materials, the most significant impact on the quality of the cut surface is the combination of input parameter. In this case, effect of cutting speed and plasma gas pressure on the roughness of the cut surface, cut perpendicularity and kerf width are analyzed.

Fig. 2. Effect of cutting speed and plasma gas pressure on surface roughness

From Fig. 2. can be seen:

- When cutting speed increases from 2000 to 2500 mm/min, the surface roughness decreases rapidly. Increasing the speed from 2500 to 3000 mm / min does not have a significant impact on surface roughness.
- When plasma gas pressure increases from 6 to 8 bar, the surface roughness increases. Increasing plasma gas pressure from 8 to 10 bar, roughness decreases.

Fig. 3. Effect of cutting speed and plasma gas pressure on cut perpendicularity

From Fig. 3. can be seen:

- When cutting speed increases from 2000 to 2500 mm/min, the cut perpendicularity decreases. Increasing the speed from 2500 to 3000 mm / min, cut perpendicularity increases.
- When plasma gas pressure increases from 6 to 8 bar, the cut perpendicularity decreases. Increasing plasma gas pressure from 8 to 10 bar, cut perpendicularity increases.

Fig. 4. Effect of cutting speed and plasma gas pressure on kerf width

From Fig. 4. can be seen:

- When cutting speed increases, kerf width decreases.
- When plasma gas pressure increases, kerf width also increases.

3.2 Grey Relational Analysis

Gray relational analysis is used for optimization multi-response characteristics. Optimization of such complicated characteristics can be converted into optimization single-response characteristic based on calculating Grey Relational Grade (GRG).

In this case, there are three response characteristics that should be minimized. These are, the surface roughness parameter R_z , cut perpendicularity and kerf width.

The first step in the grey relational analysis is that the experimental results are normalized in the range between 0 and 1. All of three quality characteristics are required to be minimized, so *smaller-is-better* approach is used. This criterion can be expressed as:

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (1)$$

where, $y_i(k)$ is the i -th eksperimental result for the k -th process responses, $\max y_i(k)$ is the largest value of $y_i(k)$, $\min y_i(k)$ is the smallest value of $y_i(k)$, and $x_i(k)$ is the normalized value of $y_i(k)$.

The normalized values of surface roughness, cut perpendicularity and kerf width calculated by (1) are shown in Table 7. After normalization, the deviation sequence was calculated by (2) and given in Table 7.

$$\Delta_{0i}(k) = |x_0(k) - x_i(k)| \quad (2)$$

where, $\Delta_{0i}(k)$ is difference of the absolute value between $x_0(k)$ and $x_i(k)$. $x_0(k)$ is the reference sequence of the k -th process response.

Exp. No.	Normalized values of responses			Deviation sequences $\Delta_{0i}(k)$		
	R_z	u	a	R_z	u	a
1.	0	0,492	0,291	1	0,508	0,709
2.	0,287	0,743	0	0,713	0,257	1
3.	0,786	0,709	0,380	0,214	0,291	0,620
4.	1	0,966	0,548	0	0,034	0,452
5.	0,695	1	0,293	0,305	0	0,707
6.	0,531	0,974	0,457	0,469	0,026	0,543
7.	0,850	0	0,832	0,150	1	0,168
8.	0,733	0,961	1	0,267	0,039	0
9.	0,637	0,770	0,419	0,363	0,230	0,581

Table 7. Normalized values and deviation sequences of responses

The next step is to determine grey relational coefficient based on normalized values of responses. The grey relational coefficients (GRC) can be calculated as:

$$\xi_i(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{0i}(k) + \zeta \Delta_{max}} \quad (3)$$

where, Δ_{min} denotes smallest value of $\Delta_{0i}(k)$, Δ_{max} denotes largest value of $\Delta_{0i}(k)$, and ζ is a distinguishing coefficient. Its value can be chosen in the range of 0 to 1. Generally, this coefficient has value of 0,5.

Average value of the Grey relational coefficients for all responses determine the Grey relational grade (GRG). Grey relational grade can be calculated by (4).

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \quad (4)$$

where, $\xi_i(k)$ is the Grey relational coefficient of k -th process response in i -th eksperiment and n is the number of process responses.

The calculated values of Grey relational coefficient and Grey relational grade are given in Table 8.

Exp. No.	Grey relational coefficient			Grey relational grade γ_i	
	R_z	u	a	γ_i	Rank
1.	0,333	0,496	0,414	0,414	9
2.	0,412	0,661	0,333	0,469	8
3.	0,700	0,632	0,446	0,593	6
4.	1	0,936	0,525	0,820	2
5.	0,621	1	0,414	0,678	3
6.	0,516	0,950	0,479	0,648	4
7.	0,769	0,333	0,748	0,617	5
8.	0,652	0,927	1	0,860	1
9.	0,580	0,685	0,462	0,576	7

Table 8. Grey relational coefficients and Grey relational grades

The higher value of Grey relational grade represents that the corresponding process responses are close to the optimal condition. In this case, it is experiment number 8 with the best combination of process parameters for surface roughness, cut perpendicularity and kerf width among 9 experiments.

The means of the Grey relational grade for each level of cutting speed and plasma gas pressure are given in Table 9. According to the results shown in Table 9, the cutting speed has the most significant effect in reducing surface roughness, cut perpendicularity and kerf width.

Level	Cutting parameters	
	A: Cutting speed	B: Plasma gas pressure
1	0,492	0,617
2	0,715	0,669
3	0,684	0,606
Δ	0,223	0,063
Rank	1	2
Total mean of Grey relational grade = 0,6305		

Table 9. Response table for the mean Grey relational grade

Fig. 5. shows the response graph for mean Grey relational grade from which the optimal combination of cutting parameters can be determined. This is the combination of parameters for which the highest mean Grey relational grade are obtained. Therefore, optimal plasma cutting parameters for X5CrNi18-10 stainless steel plates with respect to surface roughness, cut perpendicularity and kerf width are, cutting speed of $V = 2500$ mm/min and plasma gas pressure of $p = 8$ bar.

Fig. 5. Response graph for mean Grey relational grades with selected optimal cutting parameters

4. Conclusion

In this study, the Grey relational analysis was applied for optimization of the parameters of the plasma cutting process. Stainless steel X5CrNi18-10 plates with thickness of 5 mm were cut using different cutting speed and plasma gas pressure. Three output process parameters, surface roughness, cut perpendicularity and kerf width, were monitored. The optimal plasma cutting parameters are: cutting speed $V = 2500$ mm/min and plasma gas pressure $p = 8$ bar. The same parameters are recommended by the manufacturer of cutting equipment.

However, the author's recommendation is that a lower plasma gas pressure ($p = 6$ bar) can be used at the same cutting speed of 2500 mm/min, as the cut quality remains the same and lower production costs are achieved. In both cases (plasma gas pressure, $p = 6$ bar and $p = 8$ bar) the cuts belong to the same quality class according to EN ISO 9013.

The experimental result showed that the cutting speed has the most significant effect in reducing surface roughness, cut perpendicularity and kerf width.

The proposal for future research is that other input parameters (current, type of plasma gas, nozzle distance, etc.) are varied besides the cutting speed and the plasma gas pressure, and then to analyse the influence of these parameters on the cut quality for different thickness of material.

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6. References

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