



# EFFECT OF MULTI-RESPONSE PERFORMANCE CHARACTERISTICS ON OPTIMUM PLASMA ARC WELDING PROCESS PARAMETERS

J.I. Achebo

DEPARTMENT OF PRODUCTION ENGINEERING, UNIVERSITY OF BENIN, BENIN CITY, EDO STATE.  
*Email: josephachebo@yahoo.co.uk*

## Abstract

*A significant number of failures that occur in metal structures usually occur first at welded joints. Weldments are usually of lower strength than the parent metal because of certain factors such as the presence of pores due to entrapped gases, overheat treatment due to prolonged welding, brittleness of the weld as a result of weld metal oxidization, and possibly poor quality welding from operators' lack of skills. However, these inadequacies can be corrected by altering the process parameters aimed at optimizing the welding. In this research, the process parameters were optimized by applying the Taguchi method along with the Grey relational analysis. From this analysis, an optimum combination of process parameters is obtained. The optimum combination of A1B3C3D1; a torch stand-off of 4.5mm, welding current of 220A, welding speed of 500 mm/min and plasma flow rate of 2.2 litres/min, were the optimum plasma arc welding process parameter combination obtained in this study. The resulting optimal combination was further investigated by applying the Analysis of Variance, ANOVA, to show which welding process parameter significantly affected the performance characteristic of the welding process. From the ANOVA, the torch stand-off, welding speed and plasma flow rate were found to be the primary contributing factors that greatly influence welding performance whereas the welding current was considered a secondary factor. The confirmation test shows that the proposed optimum process parameters are 1.41 times better in terms of the fracture strength of the weldment, than the existing parameters. This indicates that the multiple response performance characteristics are greatly improved through this study.*

**Keywords:** weld strength, process parameters, PAW, Taguchi method with grey relational analysis

## 1. Introduction

Welding is the process of joining two or more work pieces together to form a weldment. This welding process is a much faster and economic way of joining metals when compared to casting and riveting [1]. Arc welding was developed over 200 years ago, and plasma arc welding came into use in 1964 [2]. Plasma Arc Welding is better in speed and quality than other arc welding processes and is employed by the aviation industry,

dyeing machinery manufacturing, steel pipe manufacturing, and flanged valve component manufacturing and assembly[3]. The Plasma arc welding (PAW) process was appraised in this study.

The welding current, welding speed, plasma gas flow rate, and torch stand-off, are the major process parameters that determine the strength of the weld in PAW [3,4]. There is a great demand for improving PAW performance and quality because of increasing complexity in design,

and the attendant need for strength and precision in metal works fabrication. Welds therefore need to possess equivalent strength when compared to the parent metal. The Taguchi method with grey relational analysis is used in this study to optimize the process parameters.

Other researchers who have also adopted this method are Hsiao et al [3], they optimized the plasma arc welding parameters using the Taguchi method with the grey relational analysis. Tarnng et al [5] used the grey based Taguchi methods to determine the submerged arc welding process parameters in hardfacing. Fung [6] studied the manufacturing process optimization for wear property of fiber reinforced polybutylene terephthalate composites with grey relational analysis.

Balasubramanian and Ganapathy [7] said that the grey relational analysis is a normalization evaluation technique extended to solve the complicated multi-performance characteristics that are optimized effectively. This claim was also supported by Deng [8] and Lin [9]. The relevance of this study is to produce welds of higher strength quality that can match the strength of the work piece and would meet the expected load demands than the existing quality of the welds by applying the methods used by Hsiao et al [3].

## 2. Materials and Methods

### 2.1. Materials

40mm × 40mm pieces of steel metals were joined using the PAW process. The process parameters in Table 2, arranged in the orthogonal array layout were used to conduct several welding tests. Tables 3-4 were used as the performance indicators in evaluating the postweld measurements

### 2.2. The Method used in the optimization process

Aneru et al. [10] used the steps mentioned hereunder for the optimization of process parameters using the grey relational analysis.

#### 2.2.1. Application of Taguchi method with grey relational analysis

Table 1 shows the welding process parameters in their various levels. These process parameters were substituted into Table 2 in their various levels to make weld deposits at the grooved undercut

Table 1: Welding parameters and their levels.

Factor	Variable	Level 1	Level 2	Level 3
A	Torch Stand Off (mm)	4.5	5.5	-
B	Welding Current (A)	160	180	220
C	Welding Speed (mm/min)	300	400	500
D	Plasma gas Flow rate (L/min)	2.2	2.8	3.4

Table 2: Experimental layout using an L18 orthogonal array.

Expt. No.	A Torch stand-off	B Welding current	C Welding speed	D Plasma gas flowrate
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

parts of the steel specimens to be joined, eventually producing an average of 18 experimentally iterated results containing the multi-response quality characteristics (i.e, root penetration, groove width and front undercut).

The Taguchi method involves the use of standard orthogonal arrays in its optimization processes. The L18 orthogonal array used in this study is shown in Table 2.

The performance indicators used by Hsiao et al (2008) were adopted in this study. For the welding root penetration, Table 3 was used as the indicator evaluation criteria.

Also for the Front side undercut, Table 4 was used as the performance criteria. This is used for evaluating the measured level of undercut present at the welded portions of the steel specimens.

When the welding processes have been com-

Table 3: Welding groove root penetration evaluation levels.

Root Penetration	Quantitative indicator	Evaluation Point
Incomplete Penetration	No keyhole generated due to inadequate arc force	1
Insufficient Penetration	Root penetration height < 0.5mm	2
Adequate Penetration	Root penetration height = 0.5 to 1.0mm	3
Excessive Penetration	Root penetration height > 1.0 mm	4
Penetrated Root	Welding joint can not be formed via surface tension due to excessive arc force	5

Table 4: Front-side under cut evaluation levels.

Front side under cut	Quantitative indicator	Evaluation Point
Presence of under cut	Under cut length ≥ 2mm	1
Unclear presence of undercut	Under cut length < 2mm	2
No presence of under cut	Under cut length = 0mm	3

pleted, weld deposits were made on three of the steel specimens which constituted one experimental procedure. This was repeated 18 times, resulting in a total of 54 specimens used for this study. The three different types of measurement made of the multi-response quality characteristics recorded are shown in Table 5.

The next step, was to generate the Signal-to-Noise (*S/N*) ratios,  $\eta$  for the values in Table 5. This action lead to the generation of Table 6. In generating these *S/N* ratios, two equations were used.

Equation 1 was used to determine the *S/N* ratios for the root penetration and welding groove width.

$$\eta = -10 \log \frac{\bar{y}^2}{s^2} \tag{1}$$

Where *S* = standard deviation and  $\bar{y}$  = average of experimental data for each procedure

$$s^2 = \frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n}$$

Where,  $y_i$  = evaluation indicator value of root penetration or welding groove width measured for

Table 5: Experimental results for the analysis of welding characteristic performance.

Exptl. No.	Root Penetration, mm	Groove Width, mm	Under cut, mm
1-1	2	5.4	2
1-2	3	5.6	2
1-3	2	5.5	2
2-1	1	5.6	1
2-2	4	5.7	2
2-3	3	5.5	2
3-1	3	5.4	1
3-2	1	6.2	2
3-3	1	7.3	1
4-1	4	7.3	3
4-2	4	7.6	3
4-3	2	7.4	3
5-1	3	6.4	2
5-2	2	5.8	3
5-3	3	6.2	3
6-1	2	6.3	2
6-2	3	6.5	2
6-3	2	6.1	2
7-1	5	7.4	1
7-2	3	7.3	1
7-3	4	7.2	1
8-1	4	6.5	3
8-2	3	6.0	3
8-3	4	6.4	2
9-1	2	6.6	3
9-2	3	5.9	3
9-3	2	6.8	3
10-1	3	5.3	2
10-2	2	5.4	1
10-3	4	5.5	1
11-1	2	6.3	1
11-2	3	6.4	2
11-3	2	6.7	2
12-1	1	5.8	1
12-2	2	5.9	2
12-3	3	6.1	1
13-1	4	7.2	3
13-2	3	7.4	2
13-3	4	6.8	2
14-1	3	6.5	2
14-2	3	6.4	3
14-3	2	6.5	3
15-1	3	6.8	2
15-2	2	6.4	2
15-3	3	6.7	2
16-1	4	7.3	1
16-2	5	7.4	2
16-3	4	7.6	1
17-1	2	7.2	3
17-2	4	7.3	3
17-3	3	7.2	3
18-1	2	6.3	1
18-2	3	6.7	2
18-3	4	7.2	2

Table 6: Multi-response signal-to-noise ratio for the welding performance.

Expt. No.	Root Penetration (mm), $\eta_1$	Groove Width (mm), $\eta_2$	Under cut (mm), $\eta_3$
1	-13.90	-36.57	6.0205
2	-11.30	-36.72	3.0102
3	-4.95	-18.16	1.2494
4	-10.97	-35.49	9.5468
5	-8.54	-27.28	8.0410
6	-13.89	-31.72	6.0205
7	-13.80	-39.01	0
8	-11.80	-29.29	6.9037
9	-5.44	-24.43	9.5468
10	-11.30	-36.39	1.2494
11	-13.89	-41.58	3.0102
12	-7.78	-33.53	1.2494
13	-17.82	-27.12	6.9037
14	-15.06	-42.65	8.0410
15	-15.06	-31.82	6.0205
16	-19.27	-35.49	1.2494
17	-11.30	-43.69	9.5468
18	-11.30	-25.24	3.0102

the  $i_{th}$  time and  $n =$  number of repeated experiments; here  $n = 3$ .

Equation 1 is a simplified nominal-the-better function, for which the target value is adjusted to the average value. The greater the evaluation indicator of the front undercut, a higher-the-better type, and the better it is, and its  $S/N$  ratio was determined using Eq (2).

$$\eta = -10 \log \left( \frac{1}{n} \sum_{i=0}^n \frac{1}{y_i^2} \right) \quad (2)$$

Where,  $y_i =$  evaluation indicator value of the undercut measured in the  $i^{th}$  time and  $n =$  number of repeated experiment, in this case  $n = 3$ .

In Table 6, columns 2 and 3 i.e the signal-to-noise ratio for root penetration and groove width respectively, are obtained using Eq (1) on Table 5. Also, in column 4 i.e the signal-to-noise ratio for undercut is obtained using Eq(2) on Table 5. The results therefrom are shown in Table 6.

### 2.2.2. Grey relational analysis for the $S/N$ ratio

In this analysis, the  $S/N$  ratio data in Table 6 were normalized using Eq (3). The normalized  $S/N$  ratio,  $x_{ij}$  for the  $i^{th}$  performance characteristic in the  $j^{th}$  experiment can be expressed as

$$x_{ij} = \frac{\eta_{ij} - \min_j \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}} \quad (3)$$

Where:  $\eta_{ij}$  is the  $S/N$  ratio for each parameter in each experiment,  $\min_j \eta_{ij}$  is the minimum  $S/N$

Table 7: Normalized  $S/N$  ratio for root penetration, groove width and undercut.

Expt. No.	Root Penetration (mm), $\eta_1$	Groove Width (mm), $\eta_1$	Under cut (mm), $\eta_3$
Ideal sequence	1	1	1
1	0.375	0.2789	0.6306
2	0.5566	0.2730	0.3153
3	1	1	0.1309
4	0.5796	0.3212	1
5	0.7493	0.6232	0.8423
6	0.3757	0.4689	0.6306
7	0.3820	0.1833	0
8	0.5217	0.5640	0.7231
9	0.9658	0.7544	1
10	0.5566	0.2859	0.1309
11	0.3757	0.0830	0.3153
12	0.8024	0.3980	0.1309
13	0.1013	0.5707	0.7231
14	0.2940	0.0410	0.8423
15	0.2940	0.4649	0.6306
16	0	0.3212	0.1309
17	0.5566	0	1
18	0.5560	0.7227	0.3153

ratio for each parameter in Table 6,  $\max_j \eta_{ij}$  is the maximum  $S/N$  ratio for each parameter in Table 6.

The normalized  $S/N$  ratio are presented in Table 7. In Table 7, the first row shows the best normalized  $S/N$  ratios. The larger normalized  $S/N$  ratio corresponds to the better performance and the best normalized  $S/N$  ratio is equal to unity.

The Grey relational coefficient is determined to show the relationship between the ideal (best) and actual normalized  $S/N$  ratio. The Grey relational coefficient  $\xi_{ij}$  for the  $i^{th}$  performance characteristic in the  $j^{th}$  experiment can be expressed as

$$\xi_{ij} = \frac{\min_i \min_j |x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|}{|x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|} \quad (4)$$

Where  $x_i^0 =$  ideal normalized  $S/N$  ratio for the  $i^{th}$  performance characteristic = 1.0;  $x_{ij} =$  the normalized  $S/N$  ratio obtained;  $\zeta =$  distinguishing coefficient which has value  $0 \leq \zeta \leq 1$  but usually taken as 0.5;  $\xi_{ij}$  The grey relational coefficient,  $\min_i \min_j |x_i^0 - x_{ij}| =$  the least value of  $x_i^0 - x_{ij}$  values;  $\max_i \max_j |x_i^0 - x_{ij}| =$  the maximum value of the  $x_i^0 - x_{ij}$  values.

Equation(4) is applied to Table 7 to obtain Table 8.

Table 8: Grey relational coefficient.

Expt. No.	Root Penetration (mm), $\xi_{ij}$	Groove Width (mm), $\xi_{ij}$	Under cut (mm), $\xi_{ij}$
1	0.4444	0.4095	0.5951
2	0.5300	0.4075	0.4220
3	1	1	0.4205
4	0.5432	0.4244	1
5	0.6660	0.5703	0.7602
6	0.4447	0.4849	0.5751
7	0.4472	0.3797	0.3333
8	0.5111	0.5342	0.6456
9	0.9359	0.6706	1
10	0.5300	0.4118	0.3652
11	0.4447	0.3529	0.4220
12	0.7167	0.4537	0.3652
13	0.3575	0.5380	0.6436
14	0.4146	0.3427	0.7602
15	0.4146	0.4830	0.5751
16	0.3333	0.4242	0.3652
17	0.5300	0.3333	1
18	0.5300	0.6433	0.4220

Following the above, is to convert the grey relational coefficients of each experiments in Table 8 into the grey relational grade in Table 9 by using a weighing method.

The overall evaluation of the multiple performance characteristics is based on the Grey relational grade which is obtained using Eq (5).

$$\gamma_j = \frac{1}{m} \sum_{i=1}^m w_i \xi_{ij} \tag{5}$$

Assume that:  $w_1 = w_2 = w_3 = 1$ . Where;  $\gamma_j$  = the Grey relational grade for the  $j_{th}$  experiment,  $w_i$  = the weighting factor for the  $i_{th}$  performance characteristic, and  $m$  = the number of performance characteristics (in this case, root penetration, groove width and front side undercut, ie,  $m = 3$ ).

Equation(5) is applied to Table 8 to obtain Table 9.

From Table 9, the best welding process parameters are the ones used to conduct experiment 9. Table10 is obtained from Table 9 by considering the orthogonal array setup (in Table1), this requires the taking of the respective averages of each level for the process parameters from Table 9. Table 10 shows the optimal levels of each of the welding parameters.

Total mean value of the grey relational grade = 0.5431.

From Table 10, the optimum combination of welding process parameters is  $A_1B_3C_3D_1$ . This

Table 9: Grey relational grade and its order.

Expt. No.	Grey relational Grade, $\gamma_j$	Order
1	0.4830	13
2	0.4531	14
3	0.8068	2
4	0.6558	4
5	0.6655	3
6	0.5016	11
7	0.3867	17
8	0.5636	6
9	0.8689	1
10	0.4357	15
11	0.4065	16
12	0.5119	9
13	0.5130	8
14	0.5058	10
15	0.4909	12
16	0.3742	18
17	0.6211	5
18	0.5318	7

Table 10: Response Table for the Grey relational grade.

Symbol	Process Parameter	Level 1	Level 2	Level 3	Max. - Min.
<b>A</b>	Torch stand-off	0.5983	0.4879	-	0.1104
<b>B</b>	Welding current	0.5162	0.5554	0.5577	0.0415
<b>C</b>	Welding speed	0.4747	0.5359	0.6187	0.1440
<b>D</b>	Plasma gas flowrate	0.5877	0.5103	0.5312	0.0774

result confirms the prediction made from Table 9, that Experiment 9 has the best process parameters.

The layout of Table 10 is expressed, for further clarity by presenting it in a graphical form. This leads to the construction of Figure 1. Fig 1 shows the Grey relational grade, where the dashed (center) line is the value of the total mean of the Grey relational grade. Basically, the larger the Grey relational grade, the better the multiple performance characteristics.

However, the relative importance of each of these process parameters was determined. In other words, The contribution of each of these welding process parameters to the multiple performance characteristics of the welding method were determined by obtaining the Analysis of Variance (ANOVA) in Table 11.

Equations 6-13 were used to determine the parameters in the ANOVA Table in Table 11. Sum

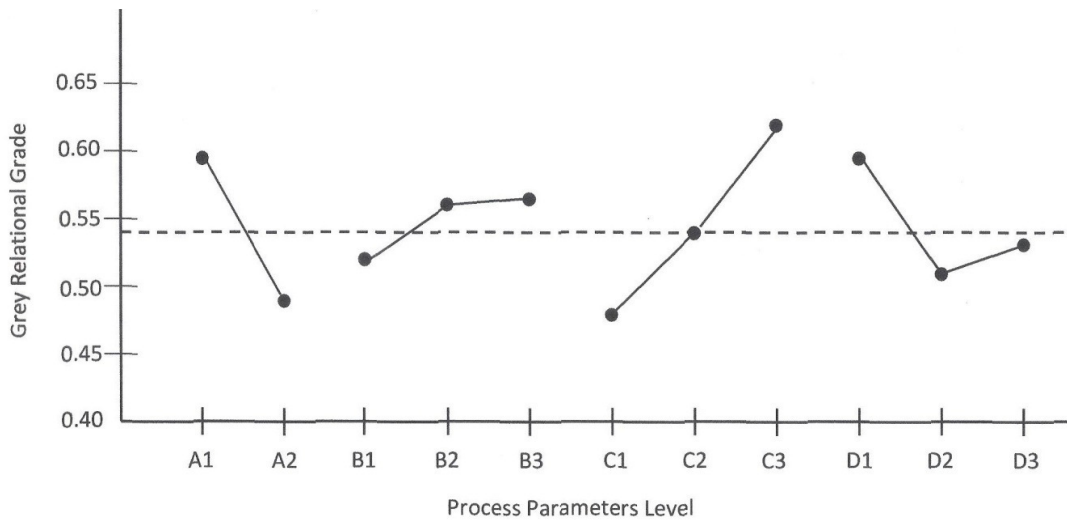


Figure 1: Grey relational grade.

Table 11: The ANOVA Table.

Variation source	DF	SS	MS	F	% Contribution
A	1	0.0549	0.0549	3.2470	17.56
B	2	0.00654	0.00327	0.1934	2.09
C	2	0.06218	0.03144	1.8595	20.11
D	2	0.01921	0.00961	0.5688	6.15
Residual	10	0.16908	0.01691		54.09
Total	17	0.33126			100.00

of Squares Total  $SS_T$ ;

$$SS_T = \sum_{i=1}^N (\gamma_i - \bar{Y})^2 \quad (6)$$

$$\bar{Y} = \sum_{i=1}^N \gamma_i \quad (7)$$

Where,  $SS_T$  is the total sum of square over the whole 18 experiments,  $\gamma_i$  is the  $i^{th}$  experiment conducted,  $\bar{Y}$  is the average of all experimental outcomes,  $N$  is the total number of experiments conducted ( $N = 18$ ).

Sum of Squares of individual process parameters  $SS_P$ ;

$$SS_P = \frac{1}{t} \sum_{j=1}^k \left( \sum \gamma_i \right)_j^2 - \frac{1}{N} \left[ \sum_{i=1}^N \gamma_i \right]^2 \quad (8)$$

Where,  $SS_P$  = Sum of squares of each process parameter,  $t$  = Number of times of each level rep-

etition,  $\sum \gamma_i$  = sum of experimental outcome for each level manipulation,  $K$  = Number of levels.

Residual Sum of Square,  $SS_R$ ;

$$SS_R = (SS_T - (SS_A + SS_B + SS_C + SS_D)) \quad (9)$$

Degree of freedom,  $Df$ ;

$$Df = n - 1 \quad (10)$$

Mean Square or Variance,  $MS$ ;

$$MS = \frac{SS_P}{Df} \quad (11)$$

Variance ratio,  $F$ ;

$$F = \frac{MS_P}{MS_R} \quad (12)$$

Percentage contribution

$$\% \text{ contr.} = \frac{SS_P}{SS_T} \times 100\% \quad (13)$$

### 3. Confirmation tests

Experiments through the Taguchi orthogonal array reveal that the optimal welding parameter combination is  $A_1B_3C_3D_1$ , which is then employed to predict the Grey relation that represents the welding quality.

Only the effects of greater significance (A, C, and D) are taken into account as predicted by

Table 12: The predicted  $S/N$  ratios and fracture strength values of optimum and existing process parameters.

	A <sub>1</sub> C <sub>3</sub> D <sub>1</sub> (Predicted optimum)	A <sub>1</sub> B <sub>3</sub> C <sub>3</sub> D <sub>1</sub> (Experimental optimum)	A <sub>2</sub> B <sub>2</sub> C <sub>3</sub> D <sub>3</sub> (Initial/existing parameter)
$S/N$ Ratio	0.7185	0.7331	0.5639
Fracture strength	481 MPa	432 MPa	342 MPa

ANOVA. Prediction of the Grey relation of the optimal welding parameters can be expressed as

$$\hat{\eta} = \eta_m + \sum_{i=1}^q (\bar{\eta}_i - \eta_m) \tag{14}$$

Where;  $\hat{\eta}$  = Grey relational grade for predicting the optimal welding parameters,  $\bar{\eta}_i$  = average Grey relational grade of the optimal level of certain significant factors A, C, and D,  $\eta_m$  = average Grey relational grade,  $q$  = number of significant factors which is 3.

Since factor B is an insignificant factor, the effect of that factor is excluded in the prediction computation. Only the effect of A<sub>1</sub>C<sub>3</sub>D<sub>1</sub> is included.

Computation of the Grey relational grade for predicting the optimal welding parameters is as follows

$$\begin{aligned} \hat{\eta} &= \eta_m + \sum_{i=1}^q (\bar{\eta}_i - \eta_m) \\ &= 0.5431 + (0.5983 - 0.5431) + (0.6187 - 0.5431) \\ &\quad + (0.5877 - 0.5431) \\ &= 0.7185 \end{aligned}$$

Finally, the confirmation test were done for the entire optimum combination of A<sub>1</sub>B<sub>3</sub>C<sub>3</sub>D<sub>1</sub>, and the existing process parameters of A<sub>2</sub>B<sub>2</sub>C<sub>3</sub>D<sub>3</sub>. The summary of the confirmation test is presented in Table 12.

From Table 12, it is shown that the  $S/N$  ratios of the predicted and experimental process parameters respectively are 1.27 and 1.30 times better than the  $S/N$  ratio of the existing welding process parameter. The fracture strengths of the predicted and experimental process parameters, respectively, are 1.41 and 1.26 times better than that of the existing welding parameter.

#### 4. Conclusions

The Taguchi method with grey relational analysis has been used to optimize the PAW process parameters. The multiresponse quality characteristics used for this study are the root penetration, groove width, and front undercut. These variables were used to determine welding performance that can produce weldment with excellent bead appearance, absence of pores, and of good quality. These features are considered to be vital determinants for increased strength in weldments.

From the Grey Relational Grade analysis, optimum combinations were suggested. In the first optimum combination, the parameter that is the least significant was eliminated based on the ANOVA evaluation results. The second optimum combination contains all the parameters. However, these combinations have shown significant improvement over the existing process parameters, in terms of the fracture strength and the multiresponse signal to noise ratios.

Summarily, the optimum process combinations have a better weld strength than the weld made by the existing process parameters. This proves that the Taguchi method with grey relational analysis can be applied to satisfactory effect.

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