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Optimization of weld bead geometry in the activated GMA welding process via a grey-based Taguchi method †

Hsuan-Liang Lin[1,*] and Jia-Ching Yan[2]

[1]*Department of Industry Technology Education, National Kaohsiung Normal University, Kaohsiung, 824, Taiwan*
[2]*Department of Mechanical Engineering, National Chiao Tung University, Hsinchu, 300, Taiwan*

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Abstract

We optimized the weld bead geometry of 6061 aluminum alloy welds pre-coated with activating flux before gas metal arc (GMA) welding. In this activated GMA welding process, there were five single component fluxes used in the initial experiment to evaluate the penetration capability of bead-on-plate GMA welds. Based on the higher penetration of weld bead, two single component fluxes were selected to create mixed component flux in next stage. The grey-based Taguchi method was employed to obtain the optimal welding parameters that were considered with multiple quality characteristics such as penetration, depth-to-width ratio (DWR) and fusion area of GMA welds. The experimental procedure of the proposed approach not only increases penetration of 6061 aluminum alloy welds, but also improves the DWR and fusion area of GMA butt-joint welds simultaneously.

Keywords: Activating flux; Aluminum alloy; GMA welding; Grey relational analysis; Taguchi method

1. Introduction

Significant efforts have been made by automotive manufacturers to meet the increasing need to reduce production costs and fuel efficiency. Weight reduction of vehicle body structures is pursued as one of the solutions to meet the requirements. To achieve a significant reduction of vehicle weight, the application of alternative lighter materials such as aluminum alloy replacing conventional steels needs to be considered [1]. In the automobile industry, gas metal arc (GMA) welding is one of the mostly applied welding processes to aluminum alloys for high welding quality and automation. Generally, the welding quality is mainly characterized by the weld bead geometry. Nagesh et al. [2] revealed that the welding quality of GMA welds is strongly characterized by the weld bead geometry. The weld bead geometry of welds plays an important role in determining the mechanical properties of the welding specimens. However, the relatively shallow penetration capability is the main disadvantage in the traditional GMA welding process. To achieve single pass welds without edge preparation, Lucas et al. [3] proposed one of the most remarkable techniques that apply a thin coating of an activating flux to the surface of base metal before welding process. Huang et al. [4] showed that oxide flux SiO_2 and multi-component flux AF305 cause an important increase in penetration on aluminum alloy in alternating current (AC) gas tungsten arc (GTA) welding process. In addition, Huang [5] found that oxide flux Fe_2O_3, SiO_2 and MgO_3 aided GMA welding increased the penetration and fusion area welds. The base metal pre-coated with MgO_3 flux produced full penetration of weld in 5 mm thick AISI 1020 carbon steel. However, many parameters influence the welding quality of GMA welds that pre-coated activating flux. Conventionally, engineers apply the Taguchi method to conduct parameter design in a variety of industrial practices. It has some limitations when adopted in practice. The Taguchi method has been designed only to optimize a single quality characteristic (QC). In this work, the grey relational analysis is used to investigate the multiple QCs in the activated GMA welding process. The grey relational analysis based on the grey system theory can be used to solve the complicated interrelationships among the multiple QCs effectively. Through the grey relational analysis, a grey relational grade is obtained to evaluate the multiple QCs, as described by Deng [6], Lin et al. [7] and Kuar et al. [8]. For example, Hsiao et al. [9] used the Taguchi method that integrated with grey relational analysis to optimize the plasma arc welding process. The undercut, root penetration and the groove width of welds were measured to identify the optimal welding parameter combination for improvement of welding quality.

To obtain the optimal welding parameters with multiple

*Corresponding author. Tel.: +886 7 7172930, Fax.: +886 7 6051206
E-mail address: hllin@nknucc.nknu.edu.tw
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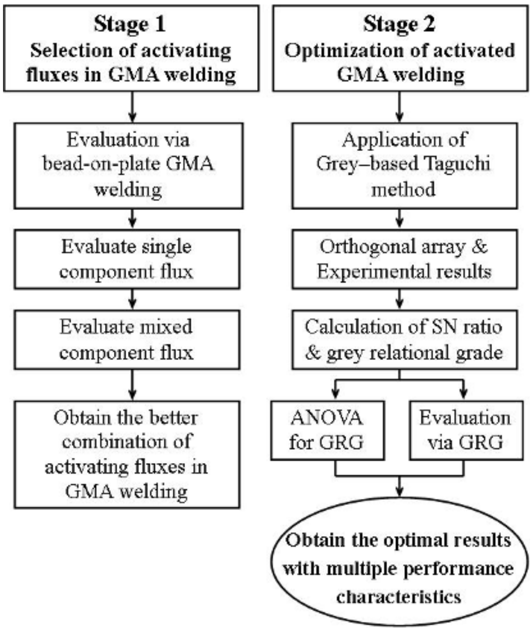


Fig. 1. Schematic diagram of experimental procedure.

QCs, this work applied an approach that integrated the Taguchi method with grey relational analysis to optimize the quality of the activated GMA welds. By the grey relational analysis, a grey relational grade is obtained to evaluate the multiple QCs. Optimization of the multiple QCs can be converted into optimization of a single grey relational grade. Therefore, the grey-based Taguchi method can simplify the optimization procedure for determining the optimal parameters in the activated GMA welding process of 6061 aluminum alloy with multiple QCs. Our purpose was to investigate the effect of activating flux on penetration capability of bead-on-plate GMA welds. A better component of activating flux was obtained in the first stage of this work. Then, the grey-based Taguchi method was used to optimize the weld bead geometry and analyze the effect of welding parameters on the 6061 aluminum alloy butt-joint welds in the activated GMA welding process. The outline of proposed approach is given in Fig. 1.

2. Experimental procedure

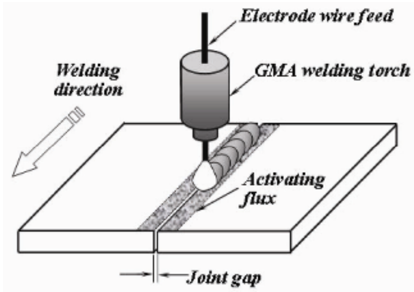
The base metal to be welded was 6061-T651 aluminum alloy. The specimens had the dimensions 60×120×6.35 mm. The electrode wire was an AWS classification ER4043 with a diameter of 1.6 mm. The chemical composition of base metal and filler metal is listed in Table 1. In the first stage of this work, there were five single component fluxes MgO, ZnO, SiO_2, MoS_2 and Na_2CO_3 used to evaluate the penetration capability of bead-on-plate GMA welds. The activating flux powder was mixed with methanol to produce paint-like consistency, a layer thickness of approximately 0.2 mm. It was applied on the 6061 aluminum alloy plate surfaces by mean of a brush before GMA welding, as shown in Fig. 2.

Table 1. Chemical concentration in base metal and electrode wire.

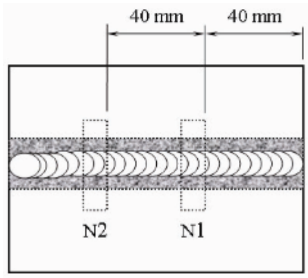
Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
6061 AA	0.8	0.7	0.4	1.5	1.2	0.35	0.25	0.15
ER4043	5	0.8	0.3	0.05	0.05	–	0.1	0.2

Table 2. Control factors and their levels.

Factor	Process parameter	Level 1	Level 2	Level 3
A	Welding voltage, V	21	22	23
B	Travel speed, mm/min	525	600	675
C	Flow rate of gas, L/min	10	15	20
D	Mixed component fluxes	25% MgO 75% ZnO	50% MgO 50% ZnO	75% MgO 25% ZnO



(a) GMA butt-joint welding produced with activating flux

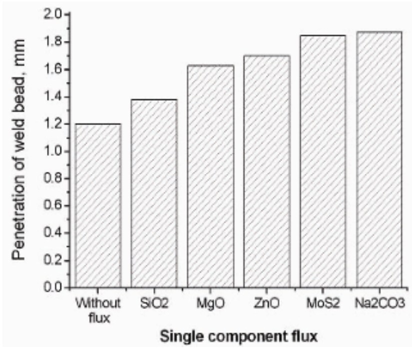


(b) The position of N1 and N2 in specimen 1

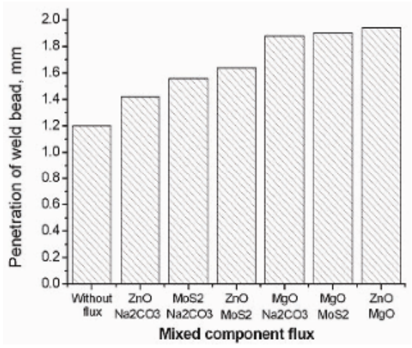
Fig. 2. Schematic diagram of the activated GMA welding process.

In the butt-joint activated GMA welding process, the joint type was a square groove, and the root opening was fixed at 1.5 mm. In the second stage, the search range of each welding parameter was as follows: welding voltage from 21 to 23 V, travel speed of welding torch from 525 to 675 mm/min, the flow rate of argon gas from 10 to 20 L/min and the weight ratio of mixed fluxes. The values of the welding process parameters at the different levels are listed in Table 2.

Measurements of the weld bead geometry were performed for evaluation of the quality of GMA welds. This work took the width of weld bead, the depth of penetration and fusion area of weld bead to describe the weld bead geometry of specimen. All specimens were prepared by mechanical lapping, grinding and polishing to a 0.3 μm finish, followed by etching in a solution containing 2 ml HF + 3 ml HCl + 5 ml HNO_3 + 190 ml H_2O. An optical microscope was used to



(a) Effect of single component flux on penetration



(b) Effect of mixed component flux on penetration

Fig. 3. Effect of activating flux on penetration of weld bead.

measure the depth, width and fusion area of GMA weld bead.

3. Results and discussion

3.1 Effect of activating flux on bead-on-plate GMA welds

The previous studies [10-12] revealed two types of action that the activating fluxes lead to an increased penetration of weld bead. These were named the Marangoni flow effect and electric arc behavior. The Marangoni flow effect is that the activating fluxes produce a positive surface tension temperature coefficient which changes the direction of the flow in the weld pool from outward to inward, thereby producing a relatively deep and narrow weld. On the other hand, the fluxes may influence the arc plasma. The dissociation and ionization of flux elements may induce a constriction of the electric arc. Fig. 3(a) shows the penetration of 6061 aluminum alloy bead-on-plate welds made by conventional GMA welding and the activated GMA welding process with different five single component fluxes. The penetration capability of activated GMA welds was obviously higher than that of the welds without flux. Based on the higher penetration of specimens as shown in Fig. 3(a), four single component fluxes were selected to mix with each other using 50% weight percent each. Then, the mixed component fluxes were used for investigating the effect to the penetration of GMA welds. Fig. 3(b) shows the penetration of GMA bead-on-plate welds using the mixed component fluxes. The penetration of mixed activating flux welds were higher than that of the welds pre-coated with single component fluxes in activated GMA welding process, with the mixed component flux 50% ZnO+50%MgO being the most significant.

Table 3. Experimental layout using L9 orthogonal array.

Trial no.	Control factor				Noise factor			
	A	B	C	D	Specimen 1		Specimen 2	
					N1	N2	N3	N4
1	1	1	1	1	Measure data			
2	1	2	2	2				
3	1	3	3	3				
4	2	1	2	3				
5	2	2	3	1				
6	2	3	1	2				
7	3	1	3	2				
8	3	2	1	3				
9	3	3	2	1				

3.2 Orthogonal array experiment

Based on the higher penetration of GMA welds, mixed component fluxes that contain MgO and ZnO fluxes were applied on the weld area of 6061 aluminum alloy plate through a layer of the activating flux to produce a butt-joint weld. The control factors are those that allow a manufacturer to control during processing, and the noise factors are expensive and difficult to control, as defined by Phadke [13]. Therefore, the welding voltage, travel speed of welding torch, flow rate of argon gas, and the weight ratio of mixed flux (MgO and ZnO oxide powder) were selected as the control factors. The fundamental principle of robust design is to improve the quality by minimizing the effect of the causes of variation. It is important in every robust design project to identify important noise factors [13]. Engineering experience and judgment are needed in identifying the noise factor. In this novel GMA welding process, it is very hard to control the layer thickness of the activating flux on the surface of base metal. Thus, the position of metallographic specimen on each specimen was selected as the noise factor, as shown in Fig. 2(b). Table 2 presents the parameters and its levels of the activated GMA welding process. The L9 orthogonal array (OA) was employed in this work, as shown in Table 3. There are 9×2=18 separate test conditions; two repetitions for each trial were planned in this experimental arrangement.

3.3 Computation of the SNR and GRG of each welding QC

The penetration, depth-to-width ratio (DWR) and fusion area of GMA butt-joint welds were selected as the quality characteristics (QCs) of the Taguchi method. They are the higher-is-better (HB) QC. The signal-to-noise ratios (SNR),

Table 4. Experiment data of L9 OA and SNR for the penetration.

Experiment	Penetration of weld bead, mm				SN ratio, dB
	Specimen 1		Specimen 2		
	N1	N2	N3	N4	
1	5.236	5.577	5.444	5.501	14.704
2	3.705	3.573	3.762	3.781	11.370
3	4.102	3.899	3.894	4.650	12.266
4	5.123	4.934	5.425	5.161	14.239
5	3.989	3.516	3.473	3.740	11.276
6	3.951	4.537	4.423	4.122	12.545
7	4.102	4.423	3.970	3.951	12.254
8	5.180	5.369	4.783	4.783	13.996
9	3.346	3.327	3.932	4.102	11.195

Table 5. Experiment data of L9 OA and SNR for the DWR.

Experiment	Depth-to-width ratio of weld bead, DWR				SN ratio, dB
	Specimen 1		Specimen 2		
	N1	N2	N3	N4	
1	0.687	0.736	0.713	0.756	-2.834
2	0.580	0.610	0.612	0.608	-4.406
3	0.666	0.565	0.626	0.846	-3.681
4	0.693	0.627	0.763	0.728	-3.131
5	0.666	0.552	0.529	0.630	-4.634
6	0.690	0.748	0.752	0.808	-2.547
7	0.490	0.483	0.615	0.633	-5.310
8	0.797	0.843	0.680	0.711	-2.508
9	0.610	0.611	0.707	0.756	-3.574

Table 6. Experiment data of L9 OA and SNR for the fusion area.

Experiment	Fusion area of weld bead, mm^2				SN ratio, dB
	Specimen 1		Specimen 2		
	N1	N2	N3	N4	
1	16.144	16.381	16.347	16.119	24.215
2	10.352	10.208	10.301	10.398	20.269
3	10.947	11.200	11.212	11.150	20.927
4	16.556	16.732	16.942	17.292	24.544
5	12.075	11.617	12.003	11.788	21.487
6	11.383	11.718	11.986	11.567	21.332
7	15.160	14.383	11.769	11.587	22.245
8	12.953	13.624	13.499	12.842	22.422
9	9.261	9.614	9.801	9.901	19.677

which condense multiple data points in a trial, depend on the characteristic that is being evaluated [14]. The equation for calculating the SNR ratio for HB characteristic is

$$SNR = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{N_i^2}\right), \tag{1}$$

Table 7. Data pre-processing and GRG for the optimization.

Experiment	Penetration	DWR	Fusion area	GRG
1	0.883	1.000	0.932	0.897
2	0.323	0.050	0.122	0.377
3	0.581	0.305	0.257	0.455
4	0.778	0.868	1.000	0.828
5	0.241	0.023	0.372	0.393
6	0.986	0.385	0.340	0.617
7	0.000	0.302	0.528	0.422
8	1.000	0.798	0.564	0.749
9	0.619	0.000	0.000	0.411

where n is the number of tests in a trial (number of repetitions regardless of noise levels), N_i is the QC of each specimen. The value of n is 4 in this study. The experimental results for the penetration, DWR and fusion area of GMA welds of each trial and its SNR are shown in Table 4, 5 and 6, respectively.

We adopted the grey relational analysis (GRA) to solve the problem of multiple QCs. The experimental results of penetration, DWR and fusion area of weld bead geometry are normalized in the range between zero and one, which is also called the grey relational generating. The normalized experimental results for the-larger-the-better characteristic can be expressed as

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}}, \tag{2}$$

where y_{ij} is the original sequence for the i_{th} experimental results in the j_{th} experiment, and x_{ij} is the sequence after the data preprocessing. Table 7 shows the normalized experimental results for the penetration, DWR and fusion area of weld bead geometry.

After data pre-processing has been carried out, a grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The grey relational coefficient δ_{ij} can be expressed as follows

$$\delta_{ij} = \frac{\min_i \min_j \left|x_i^0 - x_{ij}\right| + \varsigma \max_i \max_j \left|x_i^0 - x_{ij}\right|}{\left|x_i^0 - x_{ij}\right| + \varsigma \max_j \max_j \left|x_i^0 - x_{ij}\right|}, \tag{3}$$

where x_i^0 is the ideal normalized result for the i_{th} QCs and ς is the distinguishing coefficient, which is defined in the range $0 \le \varsigma \le 1$. Then, a weighting method is used to integrate the grey relational coefficients of each experiment into the grey relational grade (GRG). The overall evaluation of the multi-response characteristic is based on the GRG, which is given by

$$\gamma_j = \frac{1}{m}\sum_{i=1}^{m}\omega_i\delta_{ij}. \tag{4}$$

Table 8. Response table for the grey relational grade.

Factor	Process parameters	Level 1	Level 2	Level 3
A	Welding voltage	0.577	0.613	0.527
B	Travel speed	0.715	0.506	0.495
C	Flow rate of argon gas	0.754	0.539	0.423
D	Mixed component fluxes	0.567	0.472	0.677
Average grey relational grade (GRG) of total trial $\hat{\eta}$ is 0.572.				

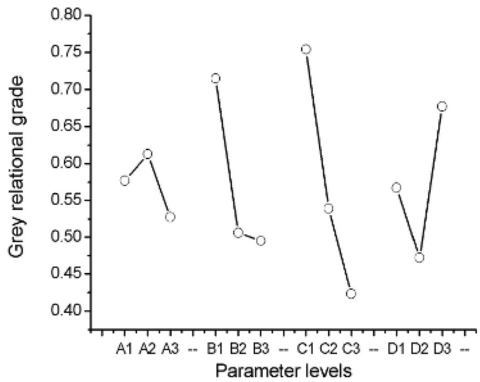


Fig. 4. GRG graph for the multiple QCs of GMA welds.

Assume that $\omega_1 = \omega_2 = 1$, where γ_j is the GRG for the j_{th} experiment, ω_i is the weighting factor for the i_{th} QC, and m is the number of QCs. Table 7 shows the GRG for each experiment using the results of L9 OA. The higher GRG represents that the corresponding experimental result is closer to the ideally normalized value. The optimization of the complicated multiple QCs can be converted into the optimization of single GRG.

3.4 Optimization via grey-based Taguchi method

The effect of each welding process parameter on GRG at different levels can be independent because the experimental design L9 OA is orthogonal. The mean of the GRG for each level of welding parameters is summarized and shown in Table 8. In other words, Fig. 4 obtained from Table 8 shows the graph of GRG with multiple QCs that considers with the penetration, DWR and fusion area of 6061 aluminum alloy GMA welds. Basically, the larger the value of grey relational grade, the better the multiple QCs for the specimens. The optimal welding combinations of the process parameter levels that consider with the multiple QCs of 6061 aluminum alloy GMA welds, $A_2B_1C_1D_3$, can be determined from Fig. 4.

The purpose of the analysis of variance (ANOVA) is to investigate welding process parameters, which can significantly affect the QCs [14]. The contribution in the total sum of the squared deviations can be used to evaluate the importance of the welding process parameter change on these QCs. The ANOVA with multiple QCs is accomplished by separating the total variability of the GRGs, which is measured by the sum of the squared deviations from the total mean of the GRG, into contributions by GMA welding parameters and the error. Results of ANOVA as shown in Table 9 indicate that the flow rate of argon gas, travel speed and the weight ratio of mixed flux are the significant welding parameters affecting the multiple QCs. The flow rate of argon gas is the most significant parameter due to its highest percentage of contribution among the activated GMA welding parameters.

Table 9. Results of ANOVA for the multiple QCs of GMA welds.

Factor	DOF #	Sum of square	Mean square	F- Test	Pure sum of square	Percent contribution
A	2	0.011 # #	-	-	-	-
B	2	0.093	0.046	8.423	0.082	24.26 %
C	2	0.170	0.085	15.426	0.159	47.16 %
D	2	0.063	0.032	5.743	0.052	15.51 %
Error	(2)	(0.011)	(0.005)		0.044	13.08 %
Total	8	0.34			0.34	100 %

DOF indicates the degree of freedom.
The factors are treated as pooled error.

3.5 Confirmation tests and validation

Table 9 reveals that control factor A has a smaller effect on the multiple QCs of the activated GMA welding process. To prevent an over-estimate [13], control factor A is not considered and the estimated SNR η_{opt} is computed as

$$\eta_{opt} = \hat{\eta} + (\overline{\eta_B} - \hat{\eta}) + (\overline{\eta_C} - \hat{\eta}) + (\overline{\eta_D} - \hat{\eta}), \tag{5}$$

where $\overline{\eta_B}$, $\overline{\eta_C}$ and $\overline{\eta_D}$ are the average grey relational grade (GRG) of the optimal level of the factors B, C and D as shown in Table 8. The proposed approach yielded the welding condition that optimized the multiple QCs of the activated GMA welding specimen: welding voltage = 22 V, travel speed of welding torch = 525 mm/min, flow rate of argon gas = 10 L/min and the weight ratio of mixed flux = 75%MgO + 25%ZnO. Table 10 presents the experimental results obtained using these optimal welding parameters. Comparing the initial conditions with the proposed approach reveals that the improvement of the GRG when the initial conditions were changed to the optimal parameters is 0.606. The experimental results as shown in Table 10 confirm that the optimization of the activated GMA welding parameters via the grey-based Taguchi method was achieved. Comparison of cross-section of GMA welds as shown in Fig. 5 reveals that the weld bead geometry of the optimal welding parameters via the proposed approach is better than that of initial conditions.

4. Conclusions

We conducted detailed experiments to investigate the effect of five single component fluxes on penetration of weld bead during the GMA welding process. The primary results showed that 6061 aluminum alloy plate pre-coated with the mixed

Table 10. Results of welding performance using the proposal approach.

Parameters & performance	Initial conditions	Grey-based Taguchi method	
		Prediction	Experiment
Welding voltage	22 V	22 V	22 V
Travel speed	600 mm/min	525 mm/min	525 mm/min
Flow rate of gas	15 L/min	10 L/min	10 L/min
Mixed fluxes	50% MgO 50% ZnO	75% MgO 25% ZnO	75% MgO 25% ZnO
Penetration	3.77 mm		6.42 mm
DWR of weld bead	0.612		0.745
Fusion area	10.35 mm ^{2}		21.99 mm ^{2}
Grey relational grade	0.381	1.002	0.989

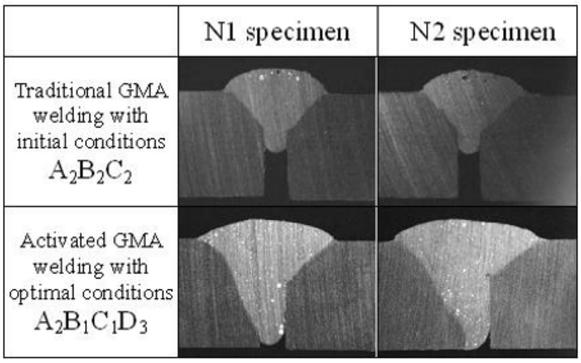


Fig. 5. Cross-sections of GMA welds for validation.

component flux 50%ZnO + 50%MgO achieves a higher increase in penetration of GMA bead-on-plate welds. Then, the Taguchi method integrated with grey relational analysis was employed to determine the activated GMA welding parameters with consideration of multiple QCs. The penetration, DWR and the fusion area of GMA butt-joint welds were measured to identify the optimal welding parameter combination via the grey-based Taguchi method. Based on ANOVA results, the flow rate of argon gas is the most significant parameter among the activated GMA welding parameters. In sum, the GMA welds pre-coated with activating flux technology have been developed successfully to weld 6.35 mm thick 6061 aluminum alloy plate via grey-based Taguchi method.

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Hsuan-Liang Lin received the Ph.D. in Mechanical Engineering from the National Chiao Tung University, Taiwan. He is an associate professor in the Department of Industry Technology Education, National Kaohsiung Normal University, Taiwan. His research activities include welding technology, vehicle engineering and quality engineering such as Taguchi method, neural network, genetic algorithm and its applications.