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APPLICATION OF GREY RELATION ANALYSIS (GRA) AND TAGUCHI METHOD FOR THE PARAMETRIC OPTIMIZATION OF FRICTION STIR WELDING (FSW) PROCESS

UPORABA GREYJEVE ANALIZE (GRA) IN TAGUCHIJEVE METODE ZA PARAMETRIČNO OPTIMIZACIJO VARJENJA Z VRTILNO-TORNIM PROCESOM (FSW)

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This study focused on the multi-response optimization of friction stir welding (FSW) process for an optimal parametric combination to yield favorable tensile strength and elongation using the Taguchi based Grey relational analysis (GRA). The objective functions have been selected in relation to parameters of FSW parameters; rotating speed, welding speed and tool shoulder diameter. The experiments were planned using Taguchi's L_8 orthogonal array. Multi-response optimization was applied using Grey relation analysis and Taguchi approach to solve the problem. The significance of the factors on overall quality characteristics of the welding process has also been evaluated quantitatively by the analysis of variance (ANOVA) method. Optimal results have been verified through confirmation experiments. This study has also showed the application feasibility of the Grey relation analysis in combination with Taguchi technique for continuous improvement in welding quality.

Keywords: Friction stir welding, Grey relation analysis, Taguchi method, optimization

Cilj raziskave je bila večodgovorna optimizacija procesa varjenja z vrtilnim trenjem (FSW) za kombinacijo parametrov za dosego ugodnih raztržne trdnosti in raztezka z uporabo Taguchi-Greyjeve racionalne analize. Primerne funkcije so bile izbrane v povezavi s FSW-parametri: hitrost vrtenja, hitrost varjenja in premer ramen orodja. Preizkusi so bili izvršeni z uporabo Taguchijeve ortogonalne mreže L_8. Odgovori so bili optimizirani z uporabo Greyjeve analize s Taguchijevim približkom. Pomen dejavnikov splošnih značilnosti procesa varjenja je bil kvantitativno analiziran z analizo variance (ANOVA). Optimalni rezultati so bili preverjeni s preizkusi. Raziskava je tudi pokazala uporabnost Greyjeve analize v povezavi s Taguchijevo tehniko za stalno izboljšanje tehnike varjenja.

Ključne besede: vrtilno torno varjenje, Greyjeva analiza odvisnosti, Taguchijeva metoda, optimizacija

1 INTRODUCTION

In today's manufacturing world, quality is of vital importance. Quality can be defined as the degree of customer's satisfaction as provided by the procured product. The product quality depends on the desired requirements gained in the product that suits its functional requirements in various areas of application.[1]

In the field of welding, weld quality mainly depends on the welding type, mechanical properties of the weld metal and heat affected zone (HAZ), which in turn is influenced by metallurgical characteristics and chemical compositions of the weld.[1] Moreover, these mechanical-metallurgical features of the weldment directly related to welding process parameters. In other words, weld quality depends on welding process parameters.[1]

The welding of aluminum and its alloys has always represented a great challenge for designers and technologists.[2] Friction stir welding (FSW) is a welding technique, patented in 1991 by TWI.[3,4]

As a solid-state process, FSW can avoid the formation of solidification cracking and porosity associated with fusion (FSW) welding processes and significantly improve the weld properties of aluminum alloys.[4,5] As illustrated in **Figure 1**, this technique involves a non-con-

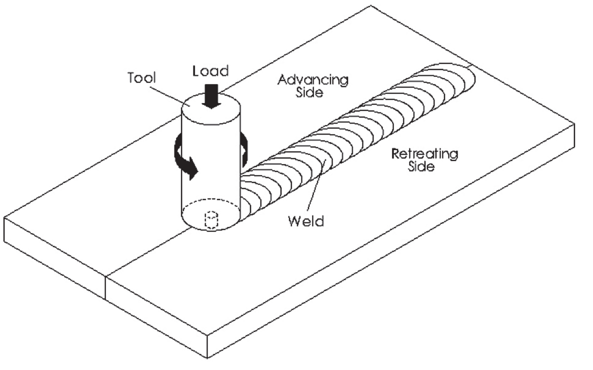

Figure 1: Schematic representation of FSW
Slika 1: Shematična predstavitev FSW

sumable, cylindrical, rotating tool (usually hardened steel) which moves between the seam of two butted plates and stirs them together.[2–6] The effect of friction stir welding on the material is both on heat flow and plastic strain. The heat is generated by friction between the tool shoulder and the top of the sheets.

When compared to traditional welding techniques, FSW strongly reduces the presence of distortions and residual stresses.[8–11] The FSW process is a solid state process and therefore a solidification structure is absent in the weld. A detailed description of the FSW process is present in the literature.[7–16] The process can be easily monitored and replicated. In addition, it does not produce any major safety hazards, such as fume or radiation.[17] This process is used to bond metals without fusion or filler materials.[18] FSW of aluminum has several advantages over fusion welding processes. Problems arising from fusion welding of aluminum alloys, such as solidification cracking, liquation cracking and porosity, are eliminated with FSW, due to its solid-state nature.[17–23]

The Taguchi method is very popular for solving optimization problems in the field of production engineering.[24,25] The method utilizes a well-balanced experimental design (allows a limited number of experimental runs) called orthogonal array design, and signal-to-noise ratio (*S/N* ratio), which serve the objective function to be optimized (maximized) within experimental domain.[24] However, traditional Taguchi method cannot solve multi-objective optimization problem. To overcome this, the Taguchi method coupled with Grey relational analysis has a wide area of application in manufacturing processes. This approach can solve multi-response optimization problem simultaneously.[26,27]

Planning the experiments through the Taguchi orthogonal array has been used quite successfully in process optimization by Chen and Chen,[28] Fung and Kang,[29] Tang et al,[30] Vijian and Arunachalam[31] as well as Zhang et al.[32] Therefore, this study applied a Taguchi L_8 orthogonal array to plan the experiments on FSW welding process. Three controlling factors including rotating speed (*w*), welding speed (*V*) and shoulder diameter (*d*) were selected. The Grey relational analysis is then applied to examine how the welding process factors influence the tensile strength (*TS*) and percent elongation (*e*). An optimal parameter combination was then obtained. Through analyzing the Grey relational grade matrix, the most influential factors for individual quality targets of FSW welding process can be identified. Additionally, the analysis of variance (ANOVA) was also utilized to examine the most significant factors for the tensile strength and elongation in FSW welding process.

2 GREY RELATIONAL ANALYSIS (GRA)

2.1 Data Preprocessing

In Grey relational analysis, experimental data i.e., measured features of quality characteristics are first normalized ranging from zero to one. This process is known as Grey relational generation. Next, based on normalized experimental data, Grey relational coefficient is calculated to represent the correlation between the desired and actual experimental data. Then overall Grey relational grade is determined by averaging the Grey relational coefficient corresponding to selected responses.[26] The overall performance characteristic of the multiple response process depends on the calculated Grey relational grade. This approach converts a multiple response process optimization problem into a single response optimization situation with the objective function is overall Grey relational grade. The optimal parametric combination is then evaluated which would result highest Grey relational grade. The optimal factor setting for maximizing overall Grey relational grade can be performed by Taguchi method.[26,33]

In Grey relational generation, the normalized E corresponding to the smaller-the-better (SB) criterion which can be expressed as:

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

TS should follow the larger-the-better (LB) criterion, which can be expressed as:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{2}$$

where $x_i(k)$ is the value after the Grey relational generation, min $y_i(k)$ is the smallest value of $y_i(k)$ for the k^{th} response, and max $y_i(k)$ is the largest value of $y_i(k)$ for the k^{th} response.[26] An ideal sequence is $x_0(k)$ (k = 1, 2, 3......, 8 for the responses. The definition of Grey relational grade in the course of Grey relational analysis is to reveal the degree of relation between the 16 sequences [$x_0(k)$ and $x_i(k)$, i = 1, 2, 3.......,8]. The Grey relational coefficient # can be calculated as:

$$\xi_i(k) = \frac{\Delta_{\min} - \psi\Delta_{\max}}{\Delta_{0i}(k) + \psi\Delta_{\max}} \tag{3}$$

where $\Delta_{0i} = \left\| x_0(k) - x_i(k) \right\|$ = difference of the absolute value $x_0(k)$ and $x_i(k)$; ψ is the distinguishing coefficient $0 \leq \psi \leq 1$; $\Delta_{\min} = \forall j^{\min} \in i \forall k^{\min} \left\| x_0(k) - x_j(k) \right\|$ = the smallest value of Δ_{0i}; and $\Delta_{\max} = \forall j^{\max} \in i \forall k^{\max} \left\| x_0(k) - x_j(k) \right\|$ = largest value of Δ_{0i}. After averaging the Grey relational coefficients, the Grey relational grade γ_i can be computed as:

$$g_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \tag{4}$$

where *n* is the number of process responses. The higher value of Grey relational grade corresponds to intense relational degree between the reference sequence $x_0(k)$ and the given sequence $x_i(k)$. The reference sequence $x_0(k)$ represents the best process sequence; therefore,

Table 1: Chemical and mechanical properties of AA1050 aluminum alloy
Tabela 1: Kemična sestava in mehanske lastnosti zlitine AA1050

Chemical composition $w/\%$	Al	Mg	Si	Mn	Zn	Fe	Ti	Sn
	Balance	0.007	0.18	0.05	0.033	0.30	0.009	0.182
Mechanical properties	Yield strength (MPa)		Tensile strength (MPa)		Elongation (%)		Vickers Hardness (*HV*)	
	155		175		4		50	

Table 2: Process parameters and their limits
Tabela 2: Parametri in limite procesa

Parameters	Notation	Unit	Levels of factors			
			1	2	3	4
Rotating speed	*w*	r/min	740*	1070	1520	2140
Welding speed	*V*	mm/min	80*	224	–	–
Shoulder diameter	*d*	mm	15*	20	–	–

*Initial factor settings

Table 3: Orthogonal array L_8 of the experimental runs and results
Tabela 3: Ortogonalna mreža L_8 eksperimentalnih varkov in rezultatov

Run no	Experimental results					
	w	*V*	*d*	*TS*/ MPa	*E*/%	Fracture location HAZ: Heat affected zone TMAZ: Thermo-mechanically affected zone NZ: Nugget zone BM: Base metal
1	1	1	1	93	14.8	The interface between HAZ and TMAZ on the retreating side
2	1	2	2	65	5.50	NZ
3	2	1	1	90	17.3	BM
4	2	2	2	89	13.5	HAZ on the retreating side
5	3	1	2	92	18.3	BM
6	3	2	1	93	14.5	HAZ on the advancing side
7	4	1	2	94	19.1	BM
8	4	2	1	92	14.1	HAZ on the advancing side

higher Grey relational grade means that the corresponding parameter combination is closer to the optimal. The mean response for the Grey relational grade with its grand mean and the main effect plot of Grey relational grade are very important because optimal process condition can be evaluated from this plot.[26]

3 EXPERIMENTAL PROCEDURE AND TEST RESULTS

3.1 Experimental Details

AA1050-H22 aluminum alloy material was used as a workpiece material with the thickness of 4 mm. The workpieces were machined out in 360 mm lengths and 200 mm widths. The mechanical properties and percent composition of workpiece material is listed in **Table 1**.

1.2367 (X38CrMoV5-3) hardened and threaded (left screw with 0.8 mm pitch) pins with the shoulder diameters of 15 mm and 20 mm were used as welding tools. The dimensions of the welding tools are shown in **Figure 2**.

The pre-machined aluminum plates were fixed rigidly on the table of the vertical semiautomatic milling machine for lap joint of FSW as shown in **Figure 3**.

The rotating tool was fixed to the spindle of the milling machine and then the spindle of the milling machine was adjusted at an angle of 2–3° away from the spindle travel path. To generate the required pre-frictional heating, the shoulder of the rotating tool was held in its ini-

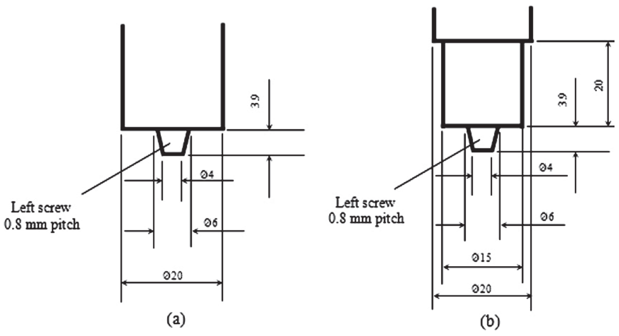

Figure 2: Dimensions of the welding tools used in the experiments: a) 20 mm shoulder diameter, b) 15 mm shoulder diameter
Slika 2: Dimenzije pri preizkusih uporabljenih varilnih orodij: a) premer ramena 20 mm, b) premer ramena 15 mm

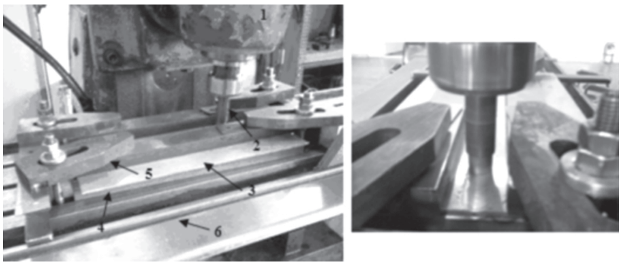

Figure 3: FSW applications on conventional vertical milling machine; 1 milling head, 2 welding tool, 3 aluminum plates, 4 Steel backing plate, 5 clamping setup, 6 machine table

Slika 3: Uporaba FSW na pokončnem vrtalnem stroju; 1 vrtalna glava, 2 varilno orodje, 3 aluminijevi plošči, 4 jeklena oporna plošča, 5 prijemno orodje, 6 delovna miza stroja

tial position for 30 s rubbing with the surface of the workpiece.

Figure 4 shows the dimensions of the tensile test specimens prepared according to TS138 EN10002-1 standard. The tensile tests were carried out at a room temperature and crosshead speed of 10 mm/min using using a ZWICK Z-050 tensile testing machine. Each tensile test is the average of four specimens cut from the same joint.

3.2 Process Parameters and Test Results

In full factorial design, the number of experimental runs exponentially increases as the number of factors as well as their level increases. This results huge experimentation cost and considerable time.[26] So, in order to compromise these two adverse factors and to search the optimal process condition through a limited number of experimental runs, Taguchi's L_8 orthogonal array consisting of 8 sets of data has been selected to optimize the multiple performance characteristics of FSW. Experiments have been conducted with the process parameters given in **Table 2**, to obtain butt welding on AA1050-H22 aluminum 4 mm thickness with (360 × 200) mm dimensions by FSW welding process.

Table 3 shows the selected design matrix based on Taguchi L_8 orthogonal array consisting of 8 sets of coded conditions and the experimental results for the responses of TS and E. All these data have been utilized for analysis and evaluation of optimal parameter combination required to achieve desired quality weld within the experimental domain.

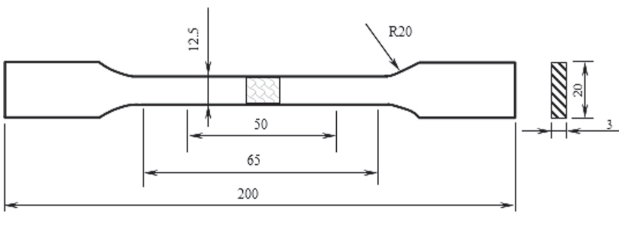

Figure 4: Dimensions of tensile test specimens

Slika 4: Dimenzije raztržnega preizkušanca

4 PARAMETRIC OPTIMIZATION OF FSW PROCESS

4.1 Evaluation of Optimal Process Condition

First, by using Eqs. (1) and (2), experimental data have been normalized to obtain Grey relational generation.[26] The normalized data and Δ_{0i} for each of the responses have been furnished in **Table 4** and **Table 5** respectively. For *TS* larger-the-better (LB) and for *E* smaller-the-better (SB) criterion has been selected.

Table 4: Grey relational generation of each performance characteristics

Tabela 4: Generiranje Greyjeve odvisnosti za značilnosti vsakega preizkusa

Run no	*TS*	*E*
	Larger-the-better	Smaller-the-better
Ideal sequence	1	1
1	0.966	0.463
2	0.000	1.000
3	0.862	0.132
4	0.828	0.412
5	0.931	0.059
6	0.966	0.338
7	1.000	0.000
8	0.931	0.368

Table 5: Evaluation of Δ_{0i} for each of the responses

Tabela 5: Ocena Δ_{0i} za vsak odgovor

Run no	*R*a	*HV*
Ideal sequence	1	1
1	0.034	0.537
2	1.000	0.000
3	0.138	0.868
4	0.172	0.588
5	0.069	0.941
6	0.034	0.662
7	0.000	1.000
8	0.069	0.632

Table 6 shows the calculated Grey relational coefficients (with the weights of $\psi_{TS} = 0.7$ and $\psi_E = 0.3$) of each performance characteristic using Eq. (3).

Table 6: Grey relational coefficient of each performance characteristics ($\psi_{TS} = 0.7$, $\psi_E = 0.3$)

Tabela 6: Greyjevi koeficienti odvisnosti za značilnosti vsakega preizkusa ($\psi_{TS} = 0.7$, $\psi_E = 0.3$)

Run no	TS	E
Ideal sequence	1	1
1	0.953	0.359
2	0.412	1.000
3	0.829	0.564
4	0.795	0.741
5	0.906	0.531
6	0.951	0.685
7	1.000	0.507
8	1.000	0.706

The Grey relational coefficients, given in **Table 7**, for each response have been accumulated by using Eq. (4) to evaluate Grey relational grade, which is the overall representative of all the features of FSW quality. Thus, the multi-criteria optimization problem has been transformed into a single equivalent objective function optimization problem using the combination of Taguchi approach and Grey relational analyses. Higher is the value of Grey relational grade, the corresponding factor combination is said to be close to the optimal[26].

Table 7: Grey relational grade
Tabela 7: Stopnje Greyjeve odvisnosti

Run no	Grey relational grade	Rank
1	0.7747	6
2	0.5882	8
3	0.7493	7
4	0.7787	5
5	0.7936	4
6	0.8710	2
7	0.8520	3
8	0.9119	1

Table 8 shows the *S/N* ratio based on the larger-the-better criterion for overall Grey relational grade calculated by using Eq. (5).

$$S/N = -10\lg\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \qquad (5)$$

where n is the number of measurements, and y_i is the measured characteristic value.

Graphical representation of S/N ratio for overall Grey relational grade is shown in **Figure 5**. The dashed line is the value of the total mean of the S/N ratio.

As indicated in **Figure 5**, the optimal condition for the FSW of aluminum alloy becomes $w_4V_1d_1$. **Table 9** shows the mean Grey relational grade ratio for each level of the process parameters.

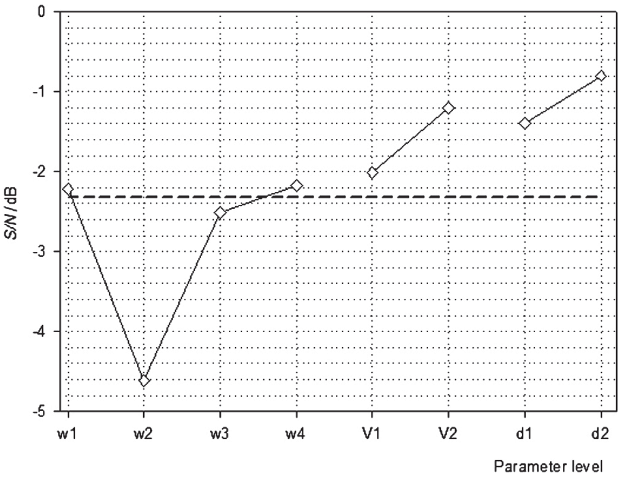

Figure 5: *S/N* ratio plot for the overall Grey relational grade
Slika 5: Razmerje *S/N* za splošno Greyjevo odvisnost

Table 8: *S/N* ratio for overall Grey relational grade
Tabela 8: Razmerje *S/N* za splošno Greyjevo stopnjo

Run no	S/N
1	–2.22
2	–4.61
3	–2.51
4	–2.17
5	–2.01
6	–1.20
7	–1.39
8	–0.80

Table 9: Response table for the mean Grey relational grade
Tabela 9: Odgovori za povprečno stopnjo po Greyu

Factors	Grey relational grade				
	Level 1	Level 2	Level 3	Level 4	Max-Min
w	0.68	0.76	0.83	0.88	0.20
V	0.79	0.78	–	–	0.01
d	0.83	0.75	–	–	0.08

Total mean Grey relational grade = 0.79

4.2 Analysis of Variance (ANOVA)

The purpose of the analysis of variance (ANOVA) is to investigate which welding parameters significantly affect the performance characteristic.[26,33,34] This is accomplished by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions by each welding parameters and the error.[26,34] Thus

$$SS_\mathrm{T} = SS_\mathrm{F} + SS_\mathrm{e} \qquad (6)$$

where

$$SS_\mathrm{T} = \sum_{j=1}^{p}(\gamma_j - \gamma_m)^2 \qquad (7)$$

and

SS_T	Total sum of squared deviations about the mean
γ_j	Mean response for jth experiment
γ_m	Grand mean of the response
p	Number of experiments in the orthogonal array
SS_F	Sum of squared deviations due to each factor
SS_e	Sum of squared deviations due to error

In addition, the F test was used to determine which welding parameters have a significant effect on the

Table 10: ANOVA results of FSW process
Tabela 10: ANOVA-rezultati FSW-procesa

Parameter	Degree of Freedom	Sum of Square	Mean Square	*F*	Contribution (%)
w	3	0.050	0.020	0.88	65.61
V	1	0.015	0.002	0.62	19.68
D	1	0.010	0.010	0.47	13.12
Error	1	0.0012	0.010		1.58
Total	6	0.0762			100

performance characteristic. Usually, the change of the welding parameter has a significant effect on the performance characteristic when the F value is large. ANOVA for overall Grey relational grade is shown in **Table 10**.

4.3 Confirmation Test

After evaluating the optimal parameter settings, the next step is to predict and verify the enhancement of quality characteristics using the optimal parametric combination. The estimated Grey relational grade $\hat{\gamma}$ using the optimal level of the design parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{o} (\bar{\gamma}_j - \gamma_m) \tag{8}$$

where γ_m is the total mean Grey relational grade, $\bar{\gamma}_i$ is the mean Grey relational grade at the optimal level, and o is the number of the main design parameters that affect the quality characteristics.[26] **Table 11** indicates the comparison of the predicted tensile strength and elongation with that of actual by using the optimal welding conditions. Good agreement between the actual and predicted results has been observed (improvement in overall Grey relational grade was found to be as 0.20).

Table 11: Results of confirmation test
Tabela 11: Rezultati preizkusov preverjanja

	Initial factor settings	Optimal process condition	
		Prediction	Experiment
Factor levels	$w_1V_1d_1$	$W_4V_1d_1$	$W_4V_1d_1$
TS	93		96
E	14.8		12.3
S/N ratio of overall Grey relational grade	–2.22	–0.58	–1.80
Overall Grey relational grade	0.72	0.89	0.92

Improvement in Grey relational grade = 0.20

In Taguchi method, the only performance feature is the overall Grey relational grade; and the aim should be to search a parameter setting that can achieve highest overall Grey relational grade.[26,33] The Grey relational grade is the representative of all individual performance characteristics. In the present study, objective functions have been selected in relation to parameters of tensile strength and elongation. The weight calculations were done by using Analytic Hierarchy Process (AHP) and the weights were found to be as 0.70 and 0.30 for the responses of tensile strength and elongation respectively.

The results showed that using optimal parameter setting ($w_4V_1d_1$) caused lower elongation with higher tensile strength.

5 CONCLUSION

Taguchi method is a very effective tool for process optimization under limited number of experimental runs. Essential requirements for all types of welding processes are higher tensile strength with lower elongation. This study has concentrated on the application of Taguchi method coupled with Grey relation analysis for solving multi criteria optimization problem in the field of friction stir welding process. Experimental results have shown that tensile strength and elongation of welded AA1050-H22 aluminum alloy are greatly improved by using Grey based Taguchi method.

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