Optimization of Friction Stir Welding Parameters of Al 6061 and Al 7075 Using GRA

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Abstract

Friction stir welding (FSW) is proved as a promising welding technology for joining dissimilar aluminium alloys. Aluminium alloys are used extensively within the aerospace industry for applications such as fuselage and wing skin panels due to their high strength to weight ratio. Therefore, an effort is made to optimize the process parameters of FSW using Al 6061 and Al 7075 alloys by the Minitab 16 program in order to enhance tensile properties such as elongation (E), yield stress (YS), and ultimate tensile strength (UTS). Grey relational analysis (GRA) based on the Taguchi method is applied using two factors tool rotational speeds (TRS) and welding speed (WS) with four levels. Results show that the variables, namely the tool rotation speed and welding speed have a significant effect on yield stress, ultimate tensile strength and elongation. Results also show that the Taguchi based grey relational approach improved properties of output response of welded Al 6061 and Al 7075 aluminum alloys.

Keyword : Friction Stir Welding FSW, Taguchi method GRA, UTS, YS, and E.

الخلاصة

لحام الخلط الاحتكاكي هو تكنولوجيا واعدة لربط سبائك الألومنيوم غير المتشابهة. سبائك الالمنيوم تستخدم بصورة شائعة في صناعات الفضاء مثل ابدان الطائرات والالواح والأجنحة نظرا لمتانته العالية نسبه الى وزنه. لذلك هنالك محاوله للوصول الى أمثليه متغيرات عمليه اللحام الاحتكاكي عند لحام سبيكتين من الالمنيوم هما6061 و7075 باستخدام برنامج Minitab 16 من اجل تحسين خصائص الشد مثل اجهاد الخضوع (YS) ومتانة الشد القصوى(UTS) ونسبة الاستطالة (E). طريقه Taguchi استخدمت كأساس لتحليل العلاقة الرمادية (GRA) باستخدام عاملين هما سرعه دوران الاداة (TRS) وسرعه اللحام (WS) بأربع مستويات. النتائج اظهرت ان المتغيرات التي هي سرعه دوران الاداة وسرعه اللحام لها تأثير كبير على اجهاد الخضوع ومتانة الشد القصوى ونسبة الاستطالة. كما اظهرت النتائج ان طريقه Taguchi المستخدمة كأساس لتحليل العلاقة الرمادية تحسن المخرجات لسبيكتي الالمنيوم 6061 7075 الملحومتان.

الكلمات المفتاحية : لحام الخلط الاحتكاكي، طريقة تاكوشي، تحليل العلاقة الرمادية، مقاومة الشد القصوى، اجهاد الخضوع ونسبة الاستطالة.

1. Introduction

Friction Stir Welding (FSW) can be used as a solid state welding method to connect aluminium sheets and plates without filler wires or shielding gas. Materials that have been successfully FS welded to date include all aluminum alloys, copper, magnesium, lead and zinc…. etc. A range of nearly all aluminum alloy classes have been successfully FS welded which include the 1xxx to 8xxx. This technique is cost saving because of good repeatability, excellent mechanical properties, high robustness and low distortion (Oliphant, 2004; Mishra *et.al.*, 2013).

Aluminum has traditionally been viewed upon as hard to weld. This is because of the low melting point and low hardness of the material. Traditional fusion welding techniques such as plasma-arc welding and metal inert gas (MIG) frequently produce negative cast microstructures in aluminium.

Huge deformations are caused by shrinkage in the weld metal and heat affected zones (HAZ). Besides, wide softening will take place in the HAZ, dropping the mechanical properties. Due to the comparatively low process temperature during FSW, approximately 0.7 to 0.9 of Tm, a large temperature gradient is avoided. Residual stresses are, therefore, kept at a low level. The pressure build-up under the tool shoulder creates a smooth weld, free of voids. Oxides and smaller inclusions are effectively disrupted and dispersed by the rotating tool. As the forces exerted by the tool are large a powerful fixture is required to hold the components in their correct position throughout the welding operation (Mishra *et.al.*, 2013;Stephen, 1991).

More recently solid-state methods for welding the material have been developed, one of these being FSW. FSW is a solid phase operation that permits the removal of the solidification defects which lead to lesser residual stresses than that of fusion welding. Moreover, FSW is well investigated for joining aluminum alloys; particularly for those frequently considered unweldable, like (6000 and 7000) series Al alloys (Kvačkaj and Bidulský, 2011).

However, several aluminum joints formed by FSW were studied by several researchers, Optimization of the FSW factors for aluminium alloy AA5083 used normally in the automotive, marine, construction and structural industries, has not yet been investigated with aid of response surface methodology (RSM). RSM is beneficial in improving an appropriate ballpark stature for the well-designed association between the independent input factors and the output factors that may idealize the quality of the joints (Manonmani *et.al.*, 2005). This has been proved by several researchers (Balasubramanian *et al.*,2008*;* Palani and Murugan, 2007; Palani and Murugan, 2006; Hung *et.al.*, 2012; Gunaraj and Murugan,1999) studied the chief problem noted in the production of pipes by the submerged arc welding operation related to the selection of the optimal interaction of input factors for attaining the desired qualities of weld. They proposed the settlement by the improvement of mathematical models through effective and strategic planning and the execution of experiments by RSM. Therefore, in this investigation, an attempt has been made to study the effect of TRS, and WS factors on the characteristics of dissimilar 6061-7075 Al alloys joint, so that the effectiveness of each factor on the tensile strength and optimal input factors of FSW operation for 6061-7075 joints could be specified.

2. 2. Experimental work

Al alloys of AA6061 and AA7075 are chosen for to produce dissimilar joints by the FSW process. The FSW machine (milling machine power has 2.2kW /440V with 2000 rev/min. and 1000 mm/min as X axis welding speed) utilized for the welding of the above Al alloy plates as shown in Figure(1) .

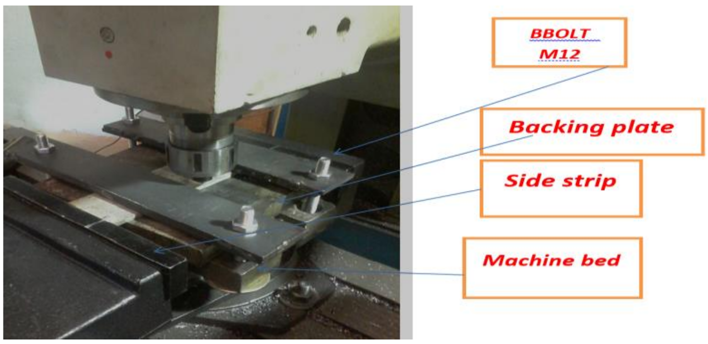

Figure 1: FSW Welding Setup.

Two Al alloys (AA6061 and AA7075) plates 6 mm thick, 100 mm length and 50 mm width with chemical compositions given in Tables 1were placed in a butt and alignment . The FSW operation was carried out normally to the trend of the plates.

Table.1 Chemical composition of Aluminum alloys.

Element(wt%)	Si	Fe	Cu	Mn	Cr	Zn	***Al***
Al- 6061	0.62	0.56	0.201	0.149	0.073	0.037	Rem.
Al-7075	0.095	0.211	0.017	0.002	0.001	1.11	Rem.

Based on initial experiments, the independent factors affecting the mechanical properties were identified as: TRS and WS therefore, the influenced factors and their levels are tabulated in Table 2.

Table 2: FSW parameters and their levels.

Actual Factors	Parameters	Unit	levels			
TRS	Tool Rotational speed	rpm	400	600	800	1000
WS	Welding speed	mm/min.	10	20	30	40

Tensile test samples were prepared as per ASTM E8 standard and transverse tensile properties like UTS, YS, and E of the FS welded joints are assessed by the computerized test machine. For welded plate, the sample is arranged and tested.

3. Results and discussion

The selected design metrics according to a Taguchi design orthogonal array (OA) are shown in Table 3. It was the two factor four levels containing 16 sets of actual conditions run which allowed the assessment of the effects the factors on the UTS, YS, and E. The value of the output is organized in Table 3.

Table 3: Matrix and assessed mechanical properties.

Exp. No	TRS (rpm)	WS (mm/min.)	YS (MPa)	UTS (MPa)	E %
1	400	10	137.20	145.51	3.52
2	400	20	135.10	143.28	3.21
3	400	30	132.44	140.46	3.00
4	400	40	130.27	138.16	2.73
5	600	10	146.70	161.14	4.22
6	600	20	144.50	158.70	3.85
7	600	30	141.61	155.55	3.60
8	600	40	139.30	153.01	3.27
9	800	10	156.80	184.10	5.92
10	800	20	154.50	181.40	4.49
11	800	30	151.36	177.70	4.20
12	800	40	148.88	174.80	3.82
13	1000	10	167.30	203.30	5.63
14	1000	20	164.80	204.25	5.13
15	1000	30	161.50	198.20	5.80
16	1000	40	158.85	145.50	4.36

3.1 Parametric Analysis of Responses

Parametric analysis of each variable on YS, UTS and E are shown in Figs. 2 - 4. It is seen that as the TRS increases the YS, UTS and E of FS welded Al 6061 and Al 7075 increases. The heat input affects the regular flow manner of the product on the other hand, low TRS generates little heat input, this lead to lack of stirring action, subsequently low strength is obtained (Colligan *et.al.,* 2003).

The YS, UTS and E tends to decrease with the increase of WS. Due to the insufficient frictional heat generated (Vijayan and Rao, 2017).

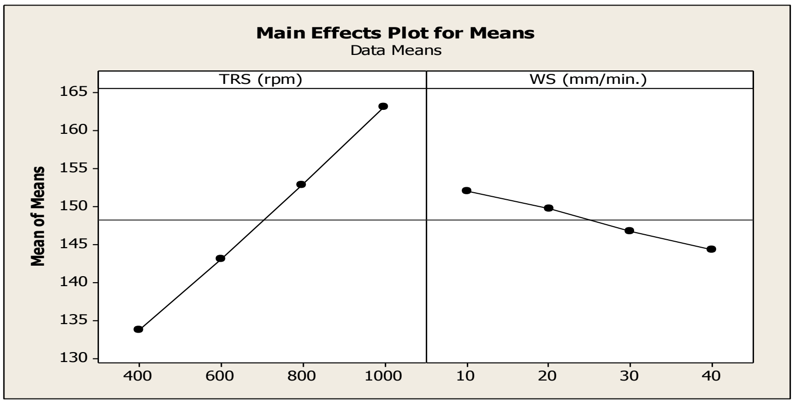

Figure 2: Main Effect Plots for YS.

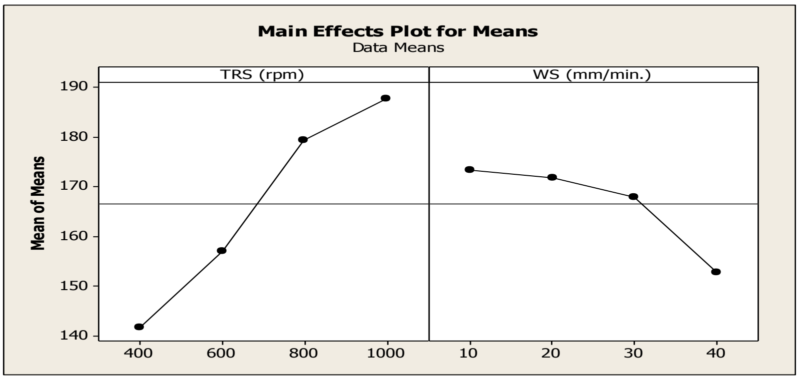

Figure 3: Main Effect Plots for UTS

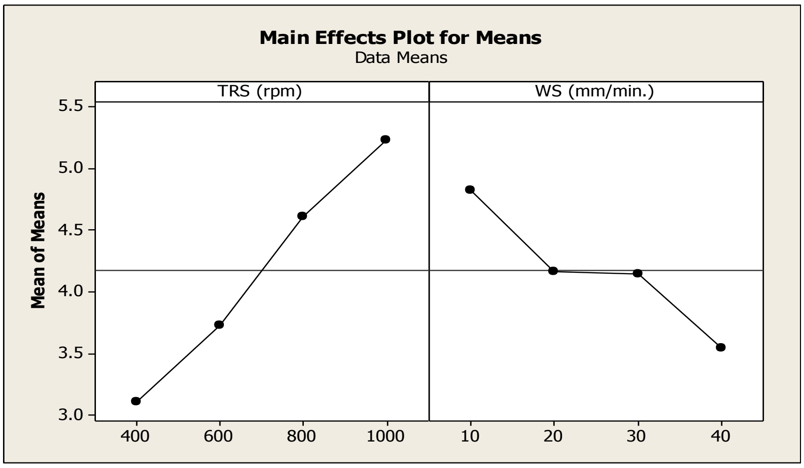

Figure 4: Main Effect Plots for E.

3.2 Checking the sufficiency of the model

The sufficiency of the models so advanced is then tested by the analysis of variance (ANOVA). Using this method, it can be noted that, as illustrated in Table 4, all the quadratic regression models significant (0 < p-value < 0.05), except WS for UTS (p-value > 0.005) and thus all the models adequately represent the experimental data.

Table 4: ANOVA Table for YS, UTS and E Second Order Models.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
For YS						
TRS	3	6.61291	6.61291	2.20430	1622096.40	0.000
WS	3	0.46686	0.46686	0.15562	114516.78	0.000
Residual Error	9	0.00001	0.00001	0.00000		
Total	15	7.07978				
For UTS						
TRS	3	14.115	14.115	4.7051	11.62	0.002
WS	3	2.817	2.817	0.9391	2.32	0.144
Residual Error	9	3.645	3.645	0.4050		
Total	15	20.577				
For E						
TRS	3	10.469	10.469	3.4897	23.71	0.000
WS	3	3.267	3.267	1.0890	7.40	0.008
Residual Error	9	1.325	1.325	0.1472		
Total	15	15.061				

The coefficient of determination (R2) is another criterion to measure the sufficiency of the model. The calculated R2 values are above 95%, 93% and 90 %, respectively as shown in Table 5. These values refer to that the regression models are quite sufficient. The validity of regression models developed is further tested by drawing scatter diagrams. Typical scatter diagrams for all the models are presented in figures. 5-7. The observed and predicted values of the responses are scattered close to the 45° line, indicating an almost perfect fit of the developed empirical models.

Table 5: R2 Test for YS, UTS and E Regression Model.

Response	R2 value	Remarks
YS	95.12 %	Adequate
UTS	93.67 %	Adequate
E	90.14 %	Adequate

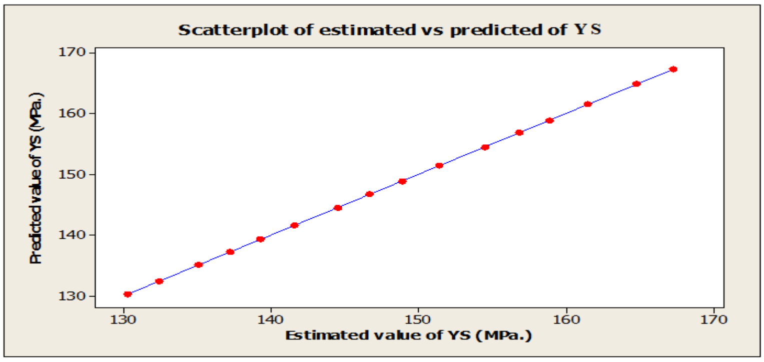

Figure 5: Scatter diagram of the YS.

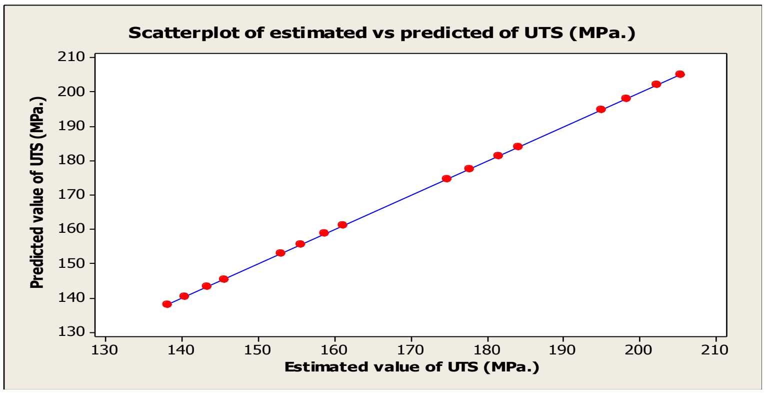

Figure 6: Scatter diagram of the UTS.

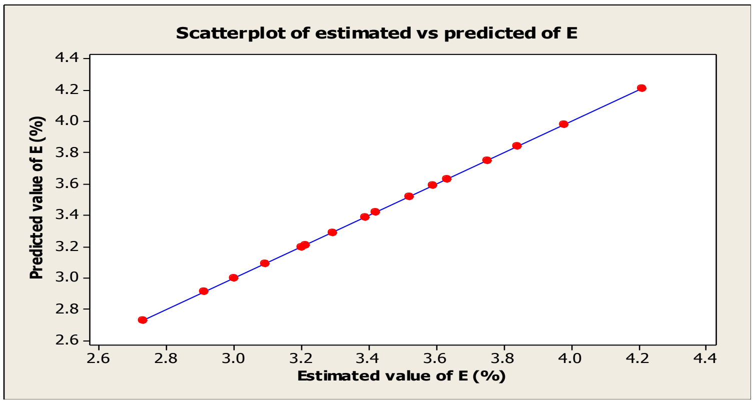

Figure 7: Scatter diagram of the E.

3.3 Optimal Welding Parameters in Grey Relation Analysis GRA

Firstly, experiments based on OA were conducted. The normalized experimental results of the responses were then introduced to find the grey relational coefficient (GRC) and degree according to GRA. Optimized factors concurrently leading to higher UTS, YS and E.

UTS, YS and E are the dominant response in FSW which determine the weldability of the response under consideration. For the "larger-the-better" characteristic such as UTS, YS and E, the initial sequence can be normalized as in equation 1 (Balasubramanian and Ganapathy, 2011):

$$x_i^*(k) = \frac{X_i(k) - \min X_i(k)}{\max X_i(k) - \min X_i(k)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where, $x_i^*(k)$ and xi (k) are the sequence after the data preprocessing and comparability sequence respectively, min xi (k) is the lowest value of xi (k) for the kth output, and max Xi(k) is the biggest value of Xi(k) for the kth response, k=1, 2 ….. n. All the sequences after data preprocessing using Eq. 1 is offered in Table 6.

Exp. No	YS (MPa)	UTS (MPa)	E %
Reference sequence	1.0000	1.0000	1.0000
1	0.187146	0.111212	0.247649
2	0.130435	0.07747	0.15047
3	0.058601	0.034801	0.084639
4	0	0	0
5	0.443694	0.347708	0.467085
6	0.384283	0.310788	0.351097
7	0.306238	0.263126	0.272727
8	0.243856	0.224694	0.169279
9	0.716446	0.695113	1
10	0.654334	0.654259	0.551724
11	0.569538	0.598275	0.460815
12	0.502565	0.554396	0.341693
13	1	0.985626	0.909091
14	0.932487	1	0.752351
15	0.84337	0.908458	0.962382
16	0.771807	0.111061	0.510972

Table 6: The sequences of each performance characteristic after data processing.

Now, the deviation sequence of the reference sequence x_0^* (k) and the comparability sequence x_i^* (k), for experiment numbers 1 to 16 by application equation 2 (Balasubramanian and Ganapathy, 2011) the results are presented in Table 7.

$$\Delta_{0i}\,(k) = |x_0^*(k) - x_i^*(k)| \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (2)$$

Δ_{0i} (k) is the deviation sequence of the reference sequence $x_0^*(k)$ and the comparability sequence $x_i^*(k)$, $\Delta_{min.}$ is minimum deviation and $\Delta\_(max.)\ \ is\ maximum$ deviation.

Table 7: The deviation sequences.

Deviation sequences	Δ0i (1)	Δ0i (2)	Δ0i (3)
Exp. no. 1	0.812854	0.888788	0.752351
Exp. no. 2	0.869565	0.92253	0.84953
Exp. no. 3	0.941399	0.965199	0.915361
Exp. no. 4	1.000000	1.000000	1.000000
Exp. no. 5	0.556306	0.652292	0.532915
Exp. no. 6	0.615717	0.689212	0.648903
Exp. no. 7	0.693762	0.736874	0.727273
Exp. no. 8	0.756144	0.775306	0.830721
Exp. no. 9	0.283554	0.304887	0.000000
Exp. no. 10	0.345666	0.345741	0.448276
Exp. no. 11	0.430462	0.401725	0.539185
Exp. no. 12	0.497435	0.445604	0.658307
Exp. no. 13	0.000000	0.014374	0.090909
Exp. no. 14	0.067513	0.000000	0.247649
Exp. no. 15	0.15663	0.091542	0.037618
Exp. no. 16	0.228193	0.888939	0.489028

After data pre-processing is performed, a GRC can be computed with the pre-processed sequence. It expresses the relation between the actual and ideal normalized experimental results. The GRC and grey relational grade (GRG) are defined depending on equations 3 and 4 (Balasubramanian and Ganapathy, 2011) (Table 8).

$$\xi_i(k) = \frac{\Delta_{min.} + \xi\Delta_{max.}}{\Delta_{oi}(k) + \xi\Delta_{max.}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3)$$

Where $\xi_i(k)$ is the GRC. ξ is distinguishing or identification coefficient. If all the parameters are given equal preference, is taken as 0.5.

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

Where $\gamma_i$the GRG for the ith experiment and n is the number of responses.

Table 8: The calculated grey relational grade and its order in the optimization process.

Exp. no.	Grey relational coefficient			Grey relational grade $\gamma i = \frac{1}{3}(\xi i(1) + \xi i(2) + \xi i(3))$	Rank
	YS $\xi i(1)$	UTS $\xi i(2)$	E $\xi i(3)$		
1	0.3808497	0.3600262	0.3992491	0.380042	13
2	0.3650794	0.3514864	0.3704994	0.362355	14
3	0.3468852	0.3412506	0.3532668	0.347134	15
4	0.3333333	0.3333333	0.3333333	0.333333	16
5	0.4733477	0.4339178	0.4840669	0.463777	9
6	0.4481423	0.4204465	0.4351977	0.434596	10
7	0.418844	0.4042449	0.4074073	0.410165	11
8	0.3980435	0.3920628	0.3757362	0.388614	12
9	0.6381181	0.6212052	1	0.753108	4
10	0.59125	0.5911975	0.5272727	0.569907	5
11	0.5373675	0.5544928	0.4811463	0.524336	6
12	0.5012858	0.5287626	0.4316645	0.487238	8
13	1	0.9720554	0.846154	0.939403	1
14	0.8810371	1	0.668763	0.849933	2
15	0.7614638	0.8452485	0.9300284	0.845580	3
16	0.6866312	0.359987	0.5055469	0.517388	7

After obtaining the GRC, the GRG is calculated by averaging the GRC corresponding to each responses. The total estimation of the multiple responses is based on the GRG; the results are shown in Table 9.

Table 9: Response table for the grey relational grade.

Symbol	FSW Para-meters	Grey relation grade				Main effect (max.-min.)	Rank
		Level 1	Level 2	Level 3	Level 4		
A	TRS	0.355716	0.424288	0.583647	0.788076*	0.43236	1
B	WS	0.634083*	0.554198	0.537912	0.431643	0.20244	2
* Levels for optimum grey relational grade							

Fundamentally, the larger the GRG is the nearer will be the product quality to the optimal value. Therefore, the larger GRG is desired for optimum responses. Thus, the optimum factors setting for larger YS, UTS and E are (A1B2) as shown in Table 9. Optimum level of the input factors is the level with the maximum GRG.

4. Conclusions

1. The FSW process is successfully used to join dissimilar Al alloys (Al6061and Al7075).
2. Better mechanical properties (YS, UTS and E) were obtained with the FS welded joint fabricated with 1000 rpm TRS and10 mm/min WS.
3. The relationships between input parameters for FSW of Al6061and Al7075 have been established. The GRA methodology was adopted to develop the regression models, which were checked for their adequacy using ANOVA test and scatter diagrams and found to be satisfactory.
4. The experiment exhibits the best factors combination and the predicted values were closer to the observed values.
5. This approach easily converts the multiple performance characteristics into the GRG, thus simplifying the analysis.
6. The results showed that the optimal condition based on the method can offer abetter overall quality.

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