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Multi Response Optimization of Friction Stir Spot Welding Process Using Taguchi Based Grey Relational Analysis

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Abstract

Friction stir spot welding (FSSW) is a solid state welding method mainly used to join non-ferrous metals and their alloys. When opposed to other welding processes, FSSW has the benefits of being pollution-free and having no filler material. In this study an attempt was made for multi response optimization of friction stir spot welded EN AW 5005 aluminum alloy using Taguchi method and Grey relational analysis (GRA). Pin height (h, mm), tool rotation (S, rpm), and welding time (t, s) were used as input parameters while tensile shear strength (TSS, MPa) and joint efficiency (JE, %) were used as multi response parameters. Therefore, Taguchi's L8 orthogonal design matrix was used in order to plan the experiments. GRA was then applied to determine the optimum condition which gives the higher grey relational degree. Analysis of Variance method (ANOVA) was also carried out in order to show the most significant parameter. Finally, confirmation test was applied to confirm the results and determine the improvement in grey relational grade throughout this method. The best results were obtained with parameters such as 2.6 mm pin height, 1500 rpm tool rotation and 10 s welding time with 122.16 MPa TSS and 111.05 JE. A significant improvement of 0.310 was obtained in the optimal parameter in grey relation grade.

Keywords: Friction stir spot welding, Aluminum alloy, Taguchi method, Grey relational analysis

Taguchi Tabanlı Gri İlişkisel Analiz Kullanılarak Sürtünme Karıştırma Nokta Kaynak İşleminin Çoklu Yanıt Optimizasyonu

Öz

Sürtünme karıştırma nokta kaynağı (SKNK), esasen demir dışı metalleri ve alaşımlarını birleştirmek için kullanılan katı hal kaynak yöntemidir. Diğer kaynak işlemlerinin aksine SKNK, kirlilikten arındırma ve dolgu malzemesine sahip olmama avantajlarına sahiptir. Bu çalışmada, Taguchi yöntemi ve Gri ilişkisel analiz (GİA) kullanılarak sürtünme karıştırma noktası kaynaklı EN AW 5005 alüminyum alaşımının çoklu yanıt optimizasyonu için bir girişimde bulunulmuştur. Girdi parametreleri olarak pim yüksekliği (h, mm), takım dönüşü (S, rpm) ve kaynak süresi (t, s) kullanılırken, çoklu yanıt olarak çekme kesme dayanımı (ÇKD, MPa) ve bağlantı performansı (% BP) kullanılmıştır. Bu nedenle, deneyleri planlamak amacıyla Taguchi'nin L8 ortogonal tasarım matrisi kullanılmıştır. Daha sonra daha yüksek gri ilişkisel

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dereceyi veren optimum koşulu belirlemek için gri ilişkisel analiz uygulanmıştır. En önemli parametrenin gösterilmesi için Varyans Analizi (ANOVA) yöntemi de yapılmıştır. Son olarak, sonuçları doğrulamak ve bu yöntem boyunca gri ilişkisel derecedeki gelişmeyi belirlemek için doğrulama testi uygulanmıştır. 122,16 MPa çekme kesme dayanımı ve 111,05 bağlantı verimi ile en iyi sonuçlar, 2,6 mm pim yüksekliği, 1500 rpm takım dönüşü ve 10 s kaynak süresi gibi parametrelerde elde edilmiştir. Gri ilişki derecesinde optimal parametrede, 0,310'luk önemli bir iyileşme elde edildi.

Anahtar Kelimeler: Sürtünme karıştırma nokta kaynağı, Alüminyum alaşımı, Taguchi yöntemi, Gri ilişkisel analiz

1. INTRODUCTION

The friction stir spot welding (FSSW) method, which is a variant of the friction stir welding (FSW) method, is a modern joint method that is commonly used in the alloy welding method for joining body structures as used in automotive industry with reduced welding times and energy consumption [1]. FSSW is a related method that may not require a filler component to add material to the cavity produced by the withdrawing tool [2,3]. So, having no filler material is one of the advantage of this method. The revolving tool is sunk to a fixed depth through the lower sheet. The tool is then placed for a brief time in the lower metal sheets before being retracted. A circular protrusion that is also called weld keyhole on the upper sheet layer is produced when a small volume of fluid is pushed out of the back after retracting the tool back. The schematic representation of the process is shown in Figure 1.

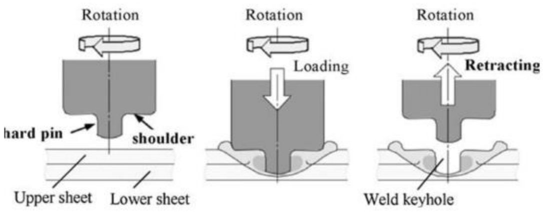


Figure 1. Schematic illustration of FSSW process [1]

In industry, there are robotic FSW implementations. For a range of factors, including their extensive use in the automobile industry, their ability to navigate three-dimensional paths frequently, and their low cost make industrial robots the ideal option for conducting FSW [3,4]. Weld processing parameters and tool geometry are thought to play a significant role in the strength of friction stir spot welds. Tool rotational speed, plunge depth, and hold time are all considerations in the welding process. Shoulder geometry and pin geometry are two examples of tool geometry combinations. Many study worked on the optimization of the FSSW process in the literature shows that the strength of the friction stir spot welded samples related to the size of the weld region and process parameter conditions [1,5,6]. Kumar et al. [7] optimized FSSW parameters for Aluminum alloys using Taguchi orthogonal array and analysis of variance (ANOVA). As a result of their studies, they determined that the rotation of the tool is the most important factor for the maximum tensile strength value. Jambhale et al. [8] using Taguchi grey based optimization method, investigated the effects of four parameters such as tool tilt angle, tool rotational speed, dwell time and tool pin profile on shear strength and microhardness in FSSW process of aluminum alloy sheets. According to ANOVA results, they reported that the most effective factor is the tool rotational speed. Raj Kumar et al. [9] used the Taguchi approach to determine the most effective process parameters that give the better tensile strength value when welding AA6063 aluminum alloy with FSSW method. They reported that parameters such as rotational speed, tool profile and axial force are the most effective factors in determining the maximum tensile strength. Abbass et al. [10] used Taguchi experimental design for optimization of the welding parameter when joining an aluminum alloy (AA5754-H114) plate with pure copper (Cu) plate using FSSW technique. They showed that maximum shear forces were obtained after welding with a straight cylindrical pin profile by taking the rotation speed of 1000 rpm and the plunging time for 90 seconds. Castro et al. [11] carried out experimental tests designed according to Taguchi method to determine the optimum welding parameters of refill FSSW and to investigate its effects on mechanical properties. The results showed that the most effective parameters on shear strength are rotational speed and tool plunge depth. Ibrahim and Yapici [12] conducted a Taguchi L_9 orthogonal array experiment design to evaluate the effect of process parameters during the joining of 2024 and 6061 aluminum alloy sheets using the FSSW method. They determined that the most effective parameter in terms of mechanical performance is the tool rotation speed. Zuo et al. [13] used a quadratic regression model with Box-Behnken design to investigate the effect of process parameters such as rotation speed, plunge depth and welding time on shear stress when combining Al/Cu two different materials with FSSW technique. As a result, they stated that the most effective factors in order of importance are rotation speed, welding time and depth of penetration, respectively. Santana et al. [14] combined 3 mm thick Al-Mg-Si alloys in Refill FSSW. They used experimental design and ANOVA for optimization of shear load. After microstructural analysis, they determined that rotation speed and plunge depth play an important role on mechanical performance. Suresh et al. [15] examined the optimum process parameters by Grey rational analysis in order to improve the weld strength in combining 6061-T6 alloy aluminum material by swept FSSW method. Their experiments were done by filling the guide hole with Taguchi L16 array with Silicon Carbide nanoparticles. As a result, it showed that the maximum shear strength and hardness value can be reached when the guide hole diameter = 3 mm, the rotation speed = 1600 rpm and the moving speed = 20 mm/min. Suryanarayanan and Sridhar [16] performed an optimization study of some process parameters in FSSW method using response surface methodology with Box-Behnken design. After ANOVA, they determined that the most effective parameter on the tensile shear force of the welded joint was the shoulder diameter, then factors such as plunge depth, plunge speed, tool rotation speed and dwell time.

The aim of this research is multi-objective optimization of the friction stir spot welded EN AW5005 aluminum alloy using Taguchi based grey relation analysis.

2. METHODOLOGY AND PROCEDURES FOR EXPERIMENTS

2.1. Experimental Details

EN AW5005 aluminum alloy with 1.5 mm thickness was cut in length of 100 mm x 25 mm. The chemical composition (percent by weight, wt.%) and mechanical properties of workpiece material is shown in Table 1. H13 hot work tool steel was used as the welding tool due to its high wear resistance and toughness at high temperatures and easy availability [3]. The welding tool of 10 mm shoulder diameter and 50 mm length and circular type tool pin profile with 2.2 mm and 2.6 mm pin height was used during the experiments. The plunge depth of 2mm was kept constant for each experiments. The tool pin profile and geometry is shown in Figure 2.

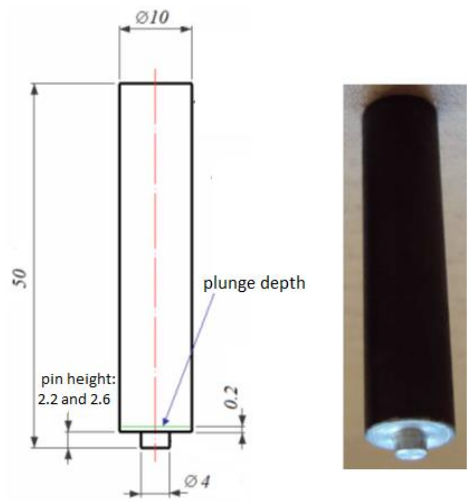


Figure 2. Tool pin profile used in the experiments

As given in Figure 3(a), the prepared workpieces were overlapped with the dimensions of 25 mm x 25 mm before the welding. Then, FSSW was performed on the vertical CNC milling machine (Figure 3(b)).

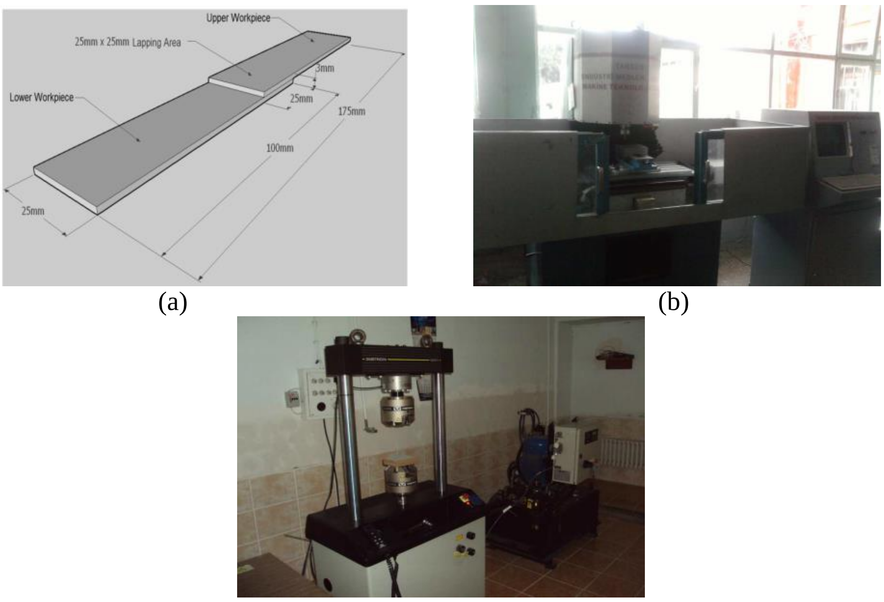
Tensile test shown in Figure 3(c) has been applied on the welded samples using INSTRON 8801 tensile testing machine and test results recorded and processed by Bluehill software.

2.2. Taguchi Design of Experiments

In the 1920s, British statistician Sir Ronald Fisher, who is known as the father of statistical science, discovered and created experimental design during his study in the field of agriculture [17,18]. Fisher is often invented the study of ANOVA technique, which is still used to analyze experimental data today. The method has been used extensively in a short period of time to improve agricultural production in the United States, and it has greatly contributed to America's leadership role in this area [17]. Dr. Genichi Taguchi is one of the people who has contributed to Japan's great quality breakthroughs from 1940s today. Dr. Taguchi is an engineer who has made significant contributions to the production of industrial products and processes in Japan.

Table 1. Chemical composition (wt.%) and mechanical properties of the workpiece

Chemical composition (wt.%)	Cr	Fe	Mn	Mg	Si	Cu	Al
	0.10	0.45	0.15	0.50-1.10	0.30	0.050	Balance
Mechanical properties	Yield strength (MPa)		Tensile strength (MPa)		Elongation (%)		Hardness (HV)
	45		110		15		32



(a) (b) (c)

Figure 3. (a) Configuration and dimensions of the workpieces, (b) FSSW process using vertical CNC milling machine, (c) Tensile testing machine

Taguchi made a name for himself in the world with the innovations he made to Ronald Fisher's experimental design process, as well as his success in the construction of the Japanese telephone system project, which was one of the most significant projects in Japan after Second World War II. Dr. Taguchi recommended using robust design and fractional factorial design approaches to complete the project in just four years. This method utilizes orthogonal design matrix which helps designer to design experiments with a limited number of trials. The signal to noise ratio (S/N) is often used in the method to serve an objective purpose within the experimental range that needs to be optimized (minimized or maximized). The Taguchi approach, on the other hand, cannot solve the multi-objective optimization problem by itself. In a broad range of engineering applications, the Taguchi method combined with Grey relational analysis (GRA) can overcome this problem and solve multi-response designed problems. This technique successfully builds optimization experiments using orthogonal arrays. In the present work, an attempt has been made for multi response modeling and optimization of FSSW responses such as tensile shear strength (TSS, Mpa) and joint efficiency (JE, %) using the input welding parameters of pin height (h, mm), tool rotation (S, rpm) and welding time (t, s).

Therefore, Taguchi's L_8 orthogonal design matrix consisting of 8 sets of data was used in order to plan the experiments. The levels of parameters is shown in Table 2.

Table 2. Parameter level of FSSW process

Parameters	Notation	Unit	Levels of parameters	
			1	2
Pin height	h	mm	2.2*	2.6
Tool rotation	S	rpm	1500*	2000
Welding time	t	s	5*	10

* Initial FSSW parameters

JE is defined as the ratio of the strength of a welded joint to the strength of the used base material. The 8 sets of coded experimental runs corresponding to TSS and JE is shown in Table 3. For the evaluation of the optimum FSSW parameter combination needed to overcome the required weld quality within the studied region, all these data were used for GRA.

Table 3. L_8 experimental run and results

Run no	Parameters			Experimental results	
	h	S	t	TSS (MPa)	JE (%)
1	1	2	1	58.92	53.56
2	1	1	1	60.66	55.15
3	1	1	2	100.71	91.55
4	2	2	1	70.86	64.42
5	1	2	2	70.27	63.88
6	2	2	2	69.66	63.33
7	2	1	1	102.70	93.36
8	2	1	2	122.16	111.05

2.3. Grey Relational Analysis (GRA) and Terminology

Although the black region of the GRA contains no data, the white region contains data completely. The grey system, on the other hand, denotes the degree of detail between black and white. In other words, although some information in the grey system is known, other information is unknown. GRA is one of the grey modeling subheadings. To decide the degree of relationship between the variables, each factor in the method was compared to a reference sequence [19].

The first step is grey relation generation which is the normalization of experimental data from 0 to 1. The Grey relational coefficient (GRC) for each experimental level is then determined using normalized values in order to establish a relationship between the actual and desired results.

Averaging the corresponding GRC for the selected answer yields the overall grey relation generation. The best parametric combination is the one with the highest grey relation generation in this method. In the present work, the larger the better (LB) criterion was used to evaluate the normalized reference sequences for ultimate TSS and JE. The LB criteria is defined as follows [19]:

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

hereby, $x_i(k)$ is obtained after grey relation generation, min $y_i(k)$ is the lowest $y_i(k)$ value of the k^{th} response, max $y_i(k)$ s the highest $y_i(k)$ value of the k^{th} response. $x_0(k)$ (k=1, 2, 3......,8) corresponds the reference series.

In the process of GRG analysis, the idea of the grey relational degree is to show the degree of the relation between 8 sequences [$x_0(k)$ and $x_i(k)$, i=1, 2, 3.......,8]. After that, the GRC $\xi_i(k)$ is defined as [19]:

$$\xi_i(k) = \frac{\Delta_{\min} - \psi\Delta_{\max}}{\Delta_{0i}(k) + \psi\Delta_{\max}} \quad (2)$$

hereby, $\Delta_{0i}=\left| x_0(k)-x_i(k) \right|$ is the absolute difference value; $\Delta_{max}=\left| x_0(k)-x_j(k) \right|$ and $\Delta_{min}=\left| x_0(k)-x_j(k) \right|$ refers to maximum and minimum difference respectively, ψ is the distinguishing coefficient $\psi\in[0,1]$, here, ψ was considered as $\psi_{UTSS}=\psi_{JE}=0.50$ for each responses.

Finally, the grey relational grade (GRG) which is the last step of the method is a calculation of the similarity degree between each factor level's comparability and reference sequences. The GRG $\Gamma(x_0,x_i)$ for each FSSW response could be determined by taking the average of GRCs as given in Equation 3 [19].

$$\Gamma(x_0, x_i) = \frac{1}{n}\sum_{k=1}^{n}\xi(x_0(k), x_i(k)) \quad (3)$$

hereby, n represents the number of responses. The higher the GRG value means the stronger the relationship between the comparison and the given series. As a result, a higher GRG implies that the associated parameter combination is extremely close to its ideal value [19].

3. RESULTS AND DISCUSSION

3.1. Determination of Optimum FSSW Condition

As a first step of GRA method, measured and calculated data were normalized using Equation 1 to obtain GRG. The normalized data and the difference of the absolute value for each of the responses have been calculated and given in Table 4.

Table 4. Normalized values and Δ_{0i} for each responses

Run	Normalization		Δ_{0i}	
	TSS	JE	TSS	E
Reference series	1.000	1.000	1.000	1.000
1	0.000	0.479	1.000	0.521
2	0.002	0.493	0.998	0.507
3	0.056	0.823	0.944	0.177
4	0.016	0.577	0.984	0.423
5	0.015	0.572	0.985	0.428
6	0.014	0.567	0.986	0.433
7	0.059	0.840	0.941	0.160
8	0.085	1.000	0.915	0.000

The distinguishing coefficient (ψ) is a number that varies from 0 to 1. According to a study of the literature, the GRG is unaffected by distinguishing factors [20]. In the present study, each response is given an equal weight of 0.50. Table 5 displays the GRCs determined using Equations 2 and 3 for each response corresponding GRG.

Table 5. Grey relation coefficient and corresponding GRG with their rank

Run	GRC ($\xi_i(k)$)		GRG ($\Gamma(x_0,x_i)$)	Rank
	TSS	JE		
1	0.250	0.390	0.320	8
2	0.250	0.396	0.323	7
3	0.261	0.653	0.457	3
4	0.253	0.441	0.347	4
5	0.253	0.438	0.345	5
6	0.253	0.435	0.344	6
7	0.261	0.675	0.468	2
8	**0.267**	**1.000**	**0.633**	**1**

It is now time to use Equation 4 given below to measure the S/N ratio based on the greater the better criterion for overall GRG [19].

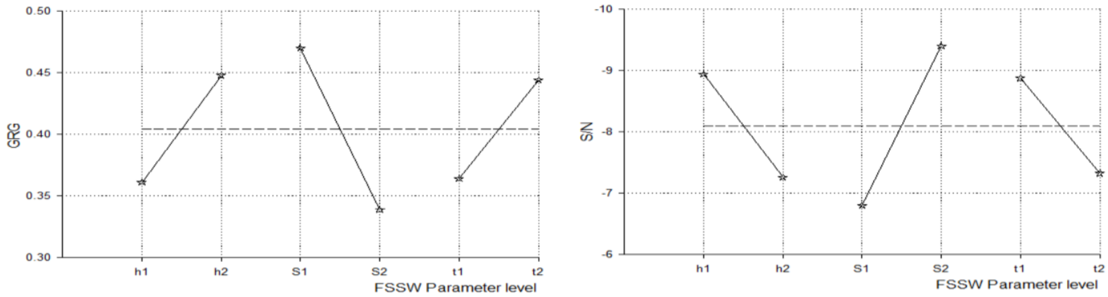
$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (4)$$

hereby, y_i is the experimental value of the i^{th} response in the experiment at the k^{th} test, and n is the number of test. Table 6 shows the conversion of GRG to S/N ratio.

Table 6. GRG and related S/N ratios

Run	GRG	S/N
1	0.320	-9.897
2	0.323	-9.816
3	0.457	-6.802
4	0.347	-9.193
5	0.345	-9.244
6	0.344	-9.269
7	0.468	-6.595
8	**0.633**	**-3.972**

The highest GRG and S/N values indicate that the setting of selected parameters is very similar to the optimum value within the experimental domain. In the present work, the highest GRG and S/N ratios of 0.633 and -3.972, respectively, for the FSSW parameter combination of; pin height at level 2, tool rotation at level 1 and welding time at level 2 ($h_2S_1t_2$) were obtained at the 8[th] experimental run. Figure 4 shows the graphical presentation of the S/N ratio and GRG versus parameter level. The average of the GRG and S/N ratio is shown by the dashed line.



(a) (b)

Figure 4. (a) Mean GRG, (b) S/N

The relative size of each impact is indicated by delta statistics, which is formulated as the maximum value minus the minimum value. In accordance with the delta analysis; tool rotation has the highest rank value, followed by pin height and welding time respectively. Table 7 illustrates the average GRG and S/N ratios for each level of average results.

Table 7. GRG and S/N mean response table

F	Mean GRG			
	L1	L2	Delta=max-min	R
h	0.361	0.448	0.086	2
S	0.470	0.339	0.131	1
t	0.364	0.444	0.080	3
Total mean GRG = 0.404				
F	S/N			
	L1	L2	Delta=max-min	R
h	-8.940	-7.257	1.682	2
S	-6.796	-9.401	2.605	1
t	-8.875	-7.322	1.554	3
Total mean S/N= -8.098, F:Factors, L:Level, R:Rank				

3.2. ANOVA Analysis

The ANOVA method is a common statistical technique used to determine the significance of each factor on the process quality characteristics. In other words, it provides a simple picture of how much each process parameter influences the response, as well as the importance of each parameter [19,21-30]. In order to indicate the importance of the parameters on the selected response, Fisher's F ratio test was used, which is the ratio of the mean of squared deviations to the mean of the squared error [17]. Table 8 depicts the ANOVA results for FSSW parameters.

Table 8. ANOVA results for FSW parameters

Parameter	Degree of freedom	Sum of square	Mean square	F ratio	Contribution (%)
h	1	0.015	0.015	69.00	17.442
S	1	0.034	0.034	157.95	39.535
t	1	0.013	0.013	59.05	15.116
hxS	1	0.011	0.011	49.87	12.791
Sxt	1	0.009	0.009	43.97	10.465
error	2	0.004	0.0002		4.651
Total	7	0.086			100
Std dev.=0.015, R-Sq=99.48%, R-Sq (adj)=98.17%, R-Sq (pred)=91.16%					

In accordance with the ANOVA analysis, it is evident that tool rotation (39.535% contribution) and pin height (17.44% contribution) are the most effective parameter while welding time (15.11% contribution) is the least effective parameter on TSS and JE. Figure 5 shows the graphical representation of percent contribution of FSSW parameters.

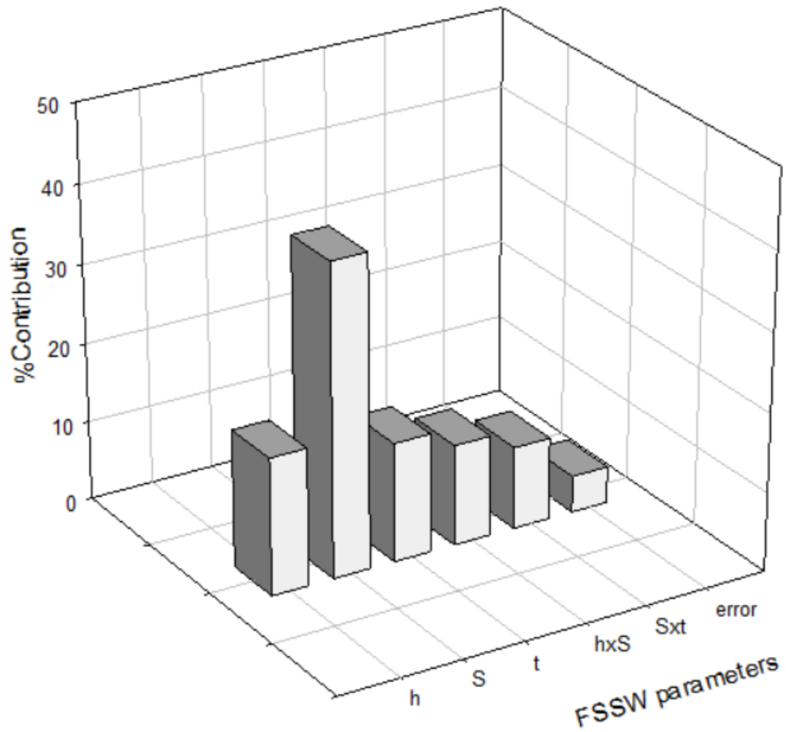


Figure 5. Contribution percentages of FSSW parameters

3.3. Confirmatory Test

The confirmatory test was carried out in this study at the optimal parameter combination ($h_2S_1t_2$) to confirm the improvement in process responses and the validity of the optimum welding condition. The predicted GRG ($\hat{\gamma}$) could be expressed as [19-21]:

$$\hat{\gamma} = \gamma_a + \sum_{i=1}^{p} (\bar{\gamma}_o - \gamma_a) \quad (5)$$

hereby, γ_a represents the total average GRG, $\bar{\gamma}_o$ represents the average GRG at the optimum level, and p represents the number of design parameters [19]. Table 9 shows the confirmation test results. It is evident from the confirmatory test results that there is a 0.310 increase in overall GRG. In FSSW process, this is the main indicator of effectiveness of the proposed Taguchi based grey relation optimization methodology. Furthermore, the method demonstrated that under the determined optimum welding condition, higher TSS of 122.16 MPa and JE of 111.05 were obtained.

Table 9. Confirmatory test results

	Initial parameter settings	Optimal FSSW condition	
		Prediction	Experiment
Optimum parameter level	$h_1S_1t_1$	$h_2S_1t_2$	$h_2S_1t_2$
Pin height (mm)	2.2	-	2.6
Tool rotation (rpm)	1500	-	1500
Welding time (s)	5	-	10
Grey relational grade	0.323	0.625	0.633
Improvement in GRG: 0.310			

4. CONCLUDING REMARKS

This research used the Taguchi based GRA approach to optimize the FSSW process parameters for EN AW-5005 aluminum alloy with 1.5 mm thickness. The following results are the conclusions that can be taken from this research:

1. The Taguchi based grey relation approach was successfully applied to FSSW of aluminum alloys.
2. The experiments were carried out successfully using Taguchi's L_8 orthogonal design array, which varied process parameters such as pin height, tool rotation, and welding time.
3. Under FSSW parameters of 2.6 mm pin height, 1500 rpm tool rotation and 10 s welding time, the best results for TSS of 122.16 MPa and JE of 111.05 were obtained.
4. The ANOVA study reveals that tool rotation (39.53%), pin height (17.44%), and welding time (15.11%) are the most important welding parameters on the responses.
5. At the optimal parameter setting, a significant improvement in GRG of 0.310 was obtained.

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