Parametric Optimization of Mechanical Properties via FSW on AA5052 Using Taguchi Based Grey Relational Analysis

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Abstract: *The Friction stir processing benefits of aluminium composites contain advanced exploration in the region of aluminium alloy Friction Stir Welding - FSW. The modern advancements in Friction Stir Welding are concentrated on the optimization of welding parameters for multi response attributes. The investigations were carried out with the tool pin profiles, tool rotational speed and traverse speed as predictable process parameters for multi response optimization in Friction Stir Welding of 5052 aluminium alloy. GRG (grey relational grade) was obtained by the grey relational analysis of the friction stir welding process through different qualities, particularly, UTS-ultimate tensile strength and micro hardness. The significant process variables on GRG and most substantial parameters traverse speed and tool pin profiles are examined by ANOVA. Excluding tool rotational speed, tool pin profiles and traverse speed were likewise observed to be significant. To approve the investigation, verification of tests was completed at optimal parameters arrangement and predicted outcomes were observed to be in great concurrence with test values.*

Key Words: *FSW, optimization, GRG and mechanical properties*

1. INTRODUCTION

FSW-Friction stir welding is a rising solid- state combination system in which the material is formed as a replacement for recasting and melting. The system was designed in 1991at the WI-The Welding Institute. Currently, materials that cannot be welded due to liquefaction could be welded through this process. FSW is the advanced process than the fusion welding process [1]. The aviation industry and present car production got innovative chances for simple and better use of the large amount accessible metal on ground. The excess of waste production in friction welding process are comparatively lesser than the conventional welding process [2]. The arrangement of flaw free FSP-friction stir processed zone is influenced by the behavior of

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flow of material in the activity of non-delicate rotating tool. The process parameters and welding tool geometry is predominantly affected by the behaviour of the material flow [3]. Campanile and Cavaliere et al. Examined outcomes on AA 6082 welded joints fabricated by FSW with the parameters contact on microstructure analysis and properties of mechanical [4]. Murali and Subramanian et al. investigated the AA7075-T6 alluminum composites mechanical properties with effect of parameters rotational speed of tool, axial load, diameter of tool shoulder, welding speed, various diameter of pin profile and hardness of tool [5]. An enormous segment of the investigations distributed are engaged around the result of FSW parameter and geometry of tool on mechanical properties and characteristic of microstructure [6–11]. Proposed reviews reveals that processing parameters such as diameter of tool shoulder, axial force, revolving speed of tool and speed of welding play a major activity in chooing the nature of welded joints [6–14].

Elangaovan and Balasubramanian et al. [12] expanded a numeric form to forecast the elongated strength of friction stir welded joints of AA 6061 by integrate Friction Stir processing parameters like axial load, tool pin profile, traverse speed and tool rotational speed. Okuyucu and Kurt et al. [13] justified the relation between FSW parameters and mechanical properties of aluminum plates by using artificial neural network method (ANN). Murugan and Sundaram [14] joined two different materials of AA 2024 and AA5083 alloy by FSW process and also made logical models using RSM to expect the strength of tensile properties and % of elongation considering rotational speed, tool axial load, different pin profile and processing speed as key parameters.

Sivasankar and Chanakyan et al. [15] obtained Friction Stir Processed AA 5052 by utilizing the numerical model to predict the mechanical properties. Vijayan and Raju et al. [16] showed the AA 5083 with several response optimization of the process parameters in FSW by L_9Taguchi technique (OA) with (GRA) grey relational analysis. From the analysis of literature, single response optimization has been carried on different aluminium alloy by FSW with various process parameters.

The insufficient of multiobjective technique is applied to identify the best output responses on AA 5052.

The current investigation is mainly focused on FSW of AA 5052 in parametric optimization by using grey relation analysis in taguchi method.

Table 1- AA5052 Chemical Composition

Portion	Fe	Si	Mn	Cu	Mg	Cr	Zn	Al
Weight in %	0.3	0.1	0.1	0	2.5	0.2	0.2	Bal

Table 2 - AA5052 Mechanical properties

Tensile strength (mpa)	% of elongation	Microhardness (Hv)
251	19	70

Table 3 - Parameters of FSW and its level

Process Parameter	Notation	Level of factors		
		1	2	3
Tool rotational speed /(rpm)	RS	800	1000	1200
Traverse speed / (mm/min)	TS	20	25	30
Different profile of tool pins	TPP	SC	PC	FC

2. EXPERIMENTATION

2.1 Range of process parameters and performance evaluation of FSW

The present studies of experiments were performed in friction stir welding machine. The mechanical properties and chemical composition of the material AA 5052 are obtainable separately, as shown in Tables 1 and 2. HCHCr (High Carbon High Chromium die Steel) was used to manufacture the friction stir welding non-consumable tool. Fabricated tool pin profiles such as a Pentagonal pin (PC), Straight cylinder (SC) and fluted cylinder (FC) are shown in Fig 1. Aluminum alloy AA 5052 plates having dimension is (100mm X 50mm X 6mm) required size [17].

Fig. 1 - Tool Pin Profiles

Square butt joint design 100 mm X 100 mm was equipped with manufactured welded joints. The welding joints were done in the framework of Single pass welding and the revolving direction was typical for the welding direction with a constant axial load of 5kN has applied for all the experiments. The process parameters working limit were verified by the trial experiments . Possible cut-off points of the welding parameters were preferred so that the welded joints were formed successfully without any deformations. In Table 3 were presented the working limits and their process parameters.

Tensile strength and Microhardness are the variable responses and welded plate of AA 5052 performance was measured. As per the standard of ASTM E8M-04 it was used to prepare the tensile specimens and testing of tensile strength were completed by using UTM. Microhardness analyzer with 0.5N loads was calculated on the area of stirring region to determine the microhardness value. In this study the characteristics of tensile strength and the hardness were observed since “larger-the-better”.

2.2 Orthogonal array (OA) Selection

In this investigation, the selected process parameter of FSW was arranged by Orthogonal array in Taguchi system. The Graeco-Latin squares were regularized the Orthogonal Array, by choosing the most appropriate Orthogonal Array for an analysis, the design and by allocating the significant interactions and parameters to the proper column. The degree of freedom is 2 [No. Of. Levels: 1 equal to Degree of freedom] and the total degree of freedom is required to select three parameters at three levels is 6 × [(3) × (3 - 1)], respectively. It is essential that the total degree of freedom greater than or equivalent to that of the preferred orthogonal array with the total DOF for conducting the experiment indicated by Taguchi's process. Table 4 provides the experimental data for each level of friction stir welding parameters throughout all the experiment. In these L9 Orthogonal Array (the three levels), having 8 Degrees of freedom was analyzed. The L9 orthogonal array stands for three columns and nine rows to perform the operation and response results ie. (Tensile strength and microhardness) represented in Table 5. Fig 2 and 3 show the welded joint specimen of AA 5052 and Prepared tensile samples.

Table 4 - Design of Experimental arrangement by using orthogonal array in L9

Runs	Tool rotational speed-RS (rpm)	Traverse speed-TS (mm/min)	Tool Pin Profiles
1	800	20	SC
2	800	25	PC
3	800	30	FC
4	1000	20	PC
5	1000	25	FC
6	1000	30	SC
7	1200	20	FC
8	1200	25	SC
9	1200	30	PC

3. EXPERIMENTAL DATA AND PRE-PROCESSING OF DATA IN GRA

The quality product was developed with the methodical use of experimental testing and design by an approach of Taguchi. In the design of experiment, Taguchi has been one of the dominant tool to develop the optimized responses. The characteristics of quality optimization were done by Taguchi analysis. The multi-performance of the process parameters were significantly optimized by the Taguchi technique by means of grey relational analysis. At GRA, mean of grey relational coefficients and the characteristics of various process in the grey relational co-efficents are determined so it is called grey relational grade (GRA). The experimental design of Taguchi has a single response in grey relational grade (GRG). The grey relational analysis was utilized to optimize the FSW parameters in the Taguchi response table. The multi responses of Friction stir welded AA5052 are tensile strength and hardness [18].

Table 5 - Response results with L9 layout

Runs	Rotational Speed-RS	Traverse speed-TS	Tool pin profiles-TPP	Tensile Strength (Mpa)	Micro hardness (Hv)
1	1	1	1	190	60
2	1	2	2	179	61
3	1	3	3	188	63
4	2	1	2	180	69
5	2	2	3	187	68
6	2	3	1	174	67
7	3	1	3	185	66
8	3	2	1	170	63
9	3	3	2	191	67

The sequence of a single data unit and the selection may change from others with required data pre-processing by the grey relational analysis. Dispersing sequence range is too huge and the sequence of target way is different, by the point pre-processing of data is required. Data preprocessing is used to transmit the process from unique sequence to similar sequence. By this reason, experimental statistics must be normalized in the range of 0 and 1 [19, 20]. In friction stir welding, the significant responses are tensile and microhardness of the welded zone, which causes the joint of welded nature is under the consideration. In favor of tensile-strength and Hv-microhardness qualities were larger-the-better, the unique sequence must be normalized as follows:

The sequences are $\mathbf{x_i}^*(\mathbf{k})$ and $\mathbf{y_i}(\mathbf{k})$,

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

subsequent to the preprocessing of data and similar sequence respectively, $\mathbf{k} = \mathbf{1}$ for tensile strength and 2 for micro hardness ie., i= $\mathbf{1, 2, 3, \ldots\ldots 9}$ for the experiment runs 1 to 9 [20] and after data preprocessing from sequences of performance characteristics by using the eqn (1) listed in Table 6.

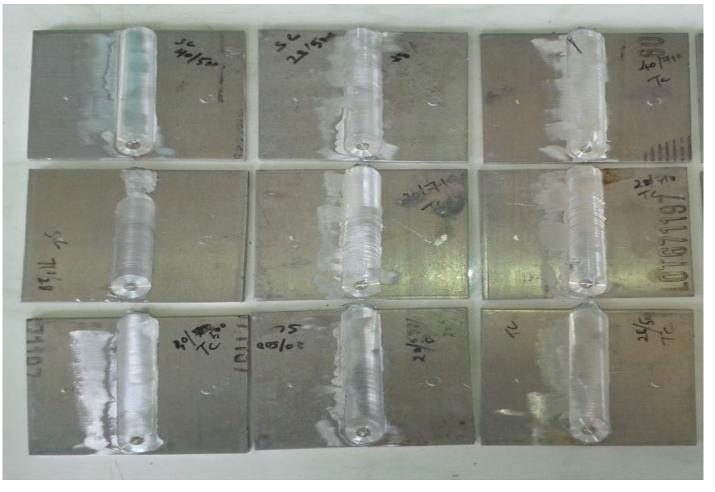

Fig. 2 - Samples of welded joints of AA5052

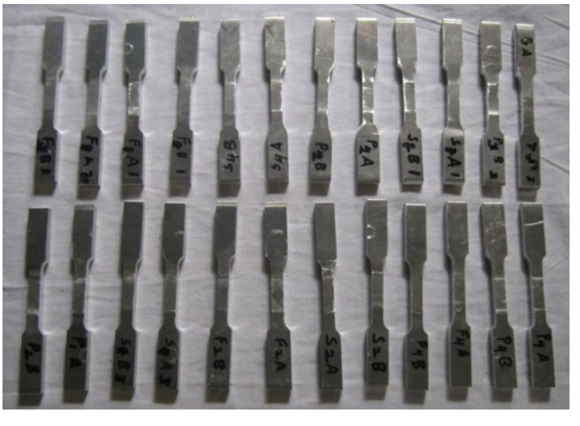

Fig. 3 - Prepared Specimen for tensile strength

3.1 Evaluating the coefficient of grey relational grade (GRG) and its ranking position

The grey relational coefficient was determined by the pre-processed sequence, after the completion of data preprocessing. The grey relation coefficient communicates the link between the preferred and valid experimental statistics. The equation of grey relational coefficient is considered below:

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

where $\Delta_{0i}(k) = \|x_0(k) - x_i(k)\|$ = differences of reference sequence $x_0[k]$ and similarity sequence $x_i[k]$ experimental data were presented in table 7. ψ is the identification coefficient. Therefore the ψ value is 0.5 and it is taken for the equal and better preference for all the parameters, to determine the grey relational coefficient with equation 2 for all the experiments of L9-OA (orthogonal array) and the value is exhibited in Table 8.

Table 6 - Standardized values of performnace qualities

Runs	Standardized Values	
	Ultimate tensile strength	Microhardness
1	0.952	0.000
2	0.429	0.200
3	0.857	0.400
4	0.476	1.000
5	0.810	0.900
6	0.190	0.800
7	0.714	0.700
8	0.000	0.400
9	1.000	0.800

Table 7 - Difference sequence of each response

Runs	Δ0i (k)	
	Ultimate Tensile strength	Microhardness
1	0.048	1.000
2	0.571	0.800
3	0.143	0.600
4	0.524	0.000
5	0.190	0.100
6	0.810	0.200
7	0.286	0.300
8	1.000	0.600
9	0.000	0.200

The characteristics of all the output performances are related to average value of grey relational coefficient. The grey relational grade was identified only after the calculation of GRC. The characteristics of overall multiple performance were calculated by grey relational grade, that is displayed in equation 3.

$$\boldsymbol{\gamma_j} = \sum_{\mathbf{k=1}}^{\mathbf{n}} \mathbf{w_i \xi_i(k)} \quad (3)$$

In the jth experiment of GRG is γ_j and the no. of execution quality is n. The L9 orthogonal array was used to analyze the grey relational grade of all experiment and it is demonstrated in table 8.

Table 8 - Computed the GRC and GRG for experimental similarity sequence

Runs	Grey relational Co-efficient (GRC)		Grey relation grade	Rank
	Ultimate tensile strength	Micro hardness		
1	0.913	0.333	0.623	5

2	0.467	0.385	0.426	8
3	0.778	0.455	0.616	6
4	0.488	1.000	0.744	3
5	0.724	0.833	0.779	2
6	0.382	0.714	0.548	7
7	0.636	0.625	0.631	4
8	0.333	0.455	0.394	9
9	1.000	0.714	0.857	1

Table 9 - GRG - Response table

Symbols	Process parameter	Grey relation Grade			(Max. value-Min Value)	Rank
		Level – (1)	Level – (2)	Level –(3)		
RS	Rotaional Speed (rpm)	0.555	0.690*	0.627	0.135	3
TS	Traverse Speed (mm/min)	0.666	0.533	0.674*	0.141	2
TPP	Tool Pin Profiles	0.522	0.676*	0.675	0.154	1
GRG total mean value = 0.624						

The results of the experimental test are nearer to the preferable standardized value showed by the higher grey relational grades. Table 8 demonstrated the best characteristics of multiple performance in the 9th experiment out of 9 experiments given that it has the maximum grey relational grade. In the current investigation, optimization of the difficult characteristics of multiple performance on FSW of AA5052 has been promoted to grey relational grade optimization. At the various levels of the grey relational grade, the outcome of all the machining parameter should be split out because the layout of experimental is orthogonal. For example, next to the levels 1, 2 and 3 of tensile strength and microhardness with grey relational grade of mean can be determined by averaging the GRG for the [1 to 3, 4 to 6 and 7 to 9] experimental runs respectively in Table 9. All the level of welding parameters is concise by using the average of GRG and revealed in the performance of multiresponse index Table 9.The overall GRG means related to the total number of 9 experiments has been calculated and displayed in Table 9. Once the larger value of GRG can be reached, the quality of product will be nearer to the perfect value. The performance of optimum must be reached only by a larger value of the grey relational grade. Along these lines, (RS2TS3TPP2) represents the tensile strength and microhardness was better when the parameter setting is optimal and it is given in Table 9. The highest value of GRG can be achieved only with the optimal condition of a process parameter level. Figure 4 exhibits the signal to noise ratio for the grey relational grade with process parameters. Figure 4 gives a clear view of maximum rotational speed of 1000 rpm achieved the higher GRG value at the 2nd level of FSW paremeter, 25mm/min of welding speed and the (PC) pentagonal pin profile has the next maximum grey relation grade at the 3rd and 2nd level, respectively. The welded joints have the similar level while best level for maximum grey relational grade can be recommended by the signal-to-noise ratio plots.

3.2 Results and Discussion

The explanation behind ANOVA is to locate the important factor measurably and it gives an unique depiction of the importance of level of the factor and the responses was influenced by the process parameters. Calculated GRG-Grey relational grade of ANOVA table is recorded in Table10. There are two parameters were significant like traverse speed and rotational speed can be initiated by analysis of the variance (ANOVA) table so as to impact the grey relational grade (GRG) and consequently, play an important part in developing the quality of tensile strength and microhardness. The 2nd level of the tool rotational speed, 3rd level of traverse speed and 2nd level of tool pin profile process parameters was the optimal condition and proved by ANOVA table as discussed above.

Table 10 - GRG ANOVA table

Basis	(DOF)	(SS)	(MS)	Contribution
Rotational Speed	2	0.07458	0.03729	28.60%
Traverse Speed	2	0.14268	0.07134	46.52%
Tool Pin Profiles	2	0.12908	0.06454	23.54%
Error	2	0.20202	0.10101	1.34%

Degree of freedom - [DoF]; Sum of square - [SS]; Mean square – [MS];

Table 11 - Correlation between experimental and predicted values with performance of welding

	The 9th experimental runs in process parameters	Optimal welding parameter condition	
		Predicted Values	Experimental values
Parameter Setting Level	RS3TS3TPP2	RS2TS3TPP2	RS2TS3TPP2
Tensile strength (mpa)	182.67	-	183.22
Micro hardness (hv)	67	-	66
Grey relational grade (GRG)	0.624	0.678	0.680

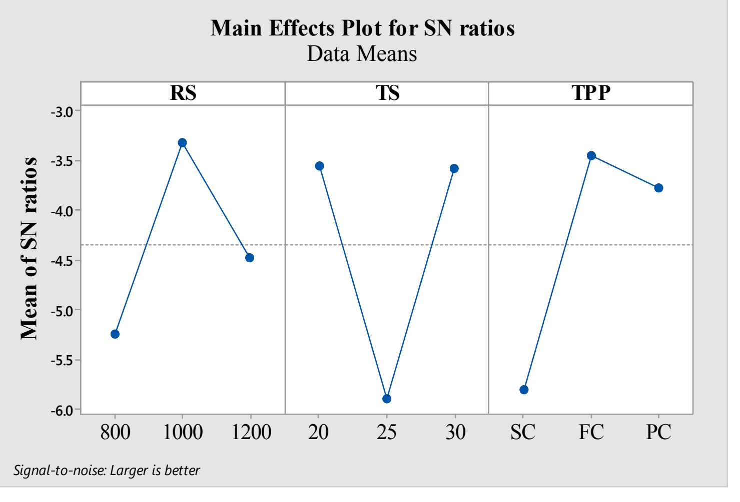

Fig. 4 - Signal to noise GRG for process parameters of welding

In the welded area of friction the processed mixture has the best characteristics together with redistribution of material and the great mixture was guided by the proper input of heat. After the FSP, cracks or pin hole deformities can be observed in that zone while the tool rotational speed is extremely low therefore tensile strength and microhardness has lower values. High rotational speed additionally causes a significant increase in instability which decreases the effects of forging and the substance strengthening at the straggling region of the FS welding elements. The grain development was guided by higher contribution of heat at exceptional low traverse speed and the tensile strength and microhardness has decreased because the processed region was influenced by increased heating between the tool and baseplate. Heat contribution was decreased by the high speed of welding which causes deformities like cracks and consequences like lower tensile strength value and lower microhardness.

3.3 Verification test

The improved performance of friction stir welded AA 5052 was confirmed by the completion of verification test. The table 9 represents the preferred optimal parameters for the verification test.

$$\hat{\mathbf{y}} = \mathbf{y_m} + \sum_{\mathbf{i=1}}^{\mathbf{q}} (\overline{\mathbf{y}}_\mathbf{i} - \mathbf{y_m}) \tag{4}$$

From the equation 4 can be utilized to calculate the predictable GRG $\hat{y}$ with the most advantageous stage of the parameters,where, the GRG total mean is indicated by y_m and by the level of optimum grey relational grade-GRG is suggested by $\overline{y_i}$. The qualities of multiple performance were influenced by significant of total number of welding parameters which is denoted by q.

The optimum level of the process parameters setting can be used to complete the verification tests and the test results of tensile strength, hardness and GRG are specified in Table 11. The primary level, expected and verification experimental runs for the values of GRG are revealed in Table 11. To achieve the grey relational grade by using verfication test equations and experimentally compared to each other. In the orhtongonal array, the 9th experiment determined the optimal welding parameters by maximizing the Grey relational grade, as shown in Table 11.

4. CONCLUSIONS

In L9 orthogonal array of Taguchi method has been applied for this experimental work. The qualities of multi-performance with the component of AA5052 FSW parameters setting were optimized by utilizing the grey relation analysis. The following points are the contribution of the present work.

1. The GRA can be utilized to optimize the process constraints of the Friction Stir welding for tensile strength of welded specimen and microhardness -Hv. The 1200rpm of the tool rotational speed, 30mm/min of traverse speed and profile of the pentagonal cylinder pin are optimal process parameters. The high tensile strength and microhardness are obtained by the suggested level of welding parameters.
2. The most prominent parameters are the rotational speed of the tool and traverse speed which can be revealed by qualities of multiple performance with grey relational grade ANOVA.
3. From the above investigation it revealed that the GRA and Taguchi systems have been used to improve the optimization of intricate qualities of multiple performance.
4. The investigation of optimum welding parameter outcome shows an improved tensile strength and a slight decrease in the microhardness. The value of 0.056 grey relational grade has been increased in the verification results.

REFERENCES

[1] A. Oosterkamp, L. Djapic Oosterkamp and A. Nordeide, Kissing Bond: Phenomena in Solid-State Welds of Aluminum Alloys, *Welding Research*, vol. **83**, no. 8, pp. 225-231, 2004.

[2] P. Praveen and P. K. D. V. Yarlagadda, Meeting challenges in welding of aluminum alloys through pulse gas metal arc welding, *Journal of Material Processing Technology*, vol. **164–165,** pp. 1106–1112, 2005.

[3] W. B. Lee and Y. M. Yeon and S. B. Jung,Mechanical properties related to microstructural variation of 6061 Al alloy joints by friction stir welding, *Materials Transaction*, vol. **45**, no. 5, pp.1700-1705, 2004.

[4] P. Cavaliere, G. Campanile, F. Panella and A. Squillace, Effect of welding parameters on mechanical and microstructural properties of AA6056 joints produced by Friction Stir Welding, *Journal of Material Processing Technology*, vol. **180**, no. 1-3, pp. 263-270, 2006.

[5] S. Rajakumar, C. Muralidharan and V. Balasubramanian, Predicting tensile strength, hardness and corrosion rate of friction stir welded AA6061-T6 aluminium alloy joints, *Materials & Design*, vol. **32**, no. 5, pp. 2878-2890, 2011.

[6] P. Cavaliere, A. Squillaceand, F.Panella, Effect of welding parameters on mechanical and microstructural properties of AA6082 joints produced by friction stir welding, *Journal of Materials Processing Technology*, vol. **200**, no. 1-3, pp. 364-372, 2008.

[7] L. Zhou, H. J. Liu and Q. W. Liu, Effect of rotation speed on microstructure and mechanical properties of Ti–6Al–4V friction stir welded joints, *Materials & Design*, vol. **31**, no. 5, pp. 2631-2636, 2010.

[8] L. Karthikeyanand, V. S. Senthil Kumar, Relationship between process parameters and mechanical properties of friction stir processed AA6063-T6 aluminum alloy, *Materials and Design*, vol. **32**, no. 5, pp. 3085-3091, 2011.

[9] K. Elangovanand, V. Balasubramanian, Influences of pin profile and rotational speed of the tool on the formation of friction stir processing zone in AA2219 aluminium alloy, *Materials Science and Engineering: A*, vol. **459**, no. 1-2,pp. 7-18, 2007.

[10] H. Fujii, L. Cui, M. Maeda and K. Nogi, Effect of tool shape on mechanical properties and microstructure of friction stir welded aluminum alloys, *Materials Science and Engineering: A*, vol. **419**, no. 1-2,25-31, 2006.

[11] T. Hirata, T. Oguri, H. Hagino, T. Tanaka, S. W. Chung, Y. Takigawa and K. Higashi, Influence of friction stir welding parameters on grain size and formability in 5083 aluminum alloy, *Materials Science and Engineering: A*, vol. **456**, no. 1-2, pp. 344-349, 2007.

[12] S. Babu, K. Elangovan and V. Balasubramanian, Optimizing friction stir welding parameters to maximize tensile strength of AA2219 aluminum alloy joints, *Metals and Material International*, vol.**15**, pp. 321-330, 2009.

[13] H. Okuyucu, A. Kurt and E. Arcaklioglu, Artificial Neural Network Application to the Friction Stir Welding of Aluminum Plates, *Materials & Design*, vol. **28**, no. 1, pp. 78-84, 2007.

[14] N. Shanmuga Sundaram and N. Murugan, Tensile Behavior of Dissimilar Friction Stir Welded Joints of Aluminium Alloys, *Materials & Design*, vol. **31**, no. 9, pp. 4184-4193, 2010.

[15] C. Chanakyan and S. Sivasankar, Parametric advancement of numerical model to predict the mechanical properties of friction stir processed AA5052, *International journal of Rapid Manufacturing*, vol. **8**, no. ½,pp. 147-160, 2019.

[16] S. Vijayan, R. Raju and S. R. Rao, Multiobjective Optimization of Friction Stir Welding Process Parameters on Aluminum Alloy AA 5083 Using Taguchi-Based Grey Relation Analysis, *Materials and Manufacturing Processes*, vol. 25, no. 11,pp. 1206-1212, 2010.

[17] C. Chanakyan, S. Sivasankar, M. Meignanamoorthy, M. Ravichandran and T. Muralidharan, Experimental investigation on influence of process parameter on friction stir processing of AA6082 using response surface methodology, *Materials Today: Proceedings*, vol. **21**, pp. 231-236, 2020.

[18] C. Chanakyan, S. Sivasankar, S. V. Alagarsamy, S. Dinesh Kumar, S. Sakthivelu, M. Meignanamoorthy and M. Ravichandran, Parametric optimization for friction stir welding with AA2024 and AA6061 aluminium alloys by ANOVA and GRG, *Materials Today: Proceedings*, vol. **27**, pp. 707-711, 2020.

[19] J. Deng, Control problems of grey systems, *Systems & Control Letters*, vol. **1**, pp. 288-294, 1982.

[20] U. Caydasand, A. Hascalik, Use of the grey relational analysis to determine optimum laser cutting parameters with multi-performance characteristics, *Optics & Laser Technology*, vol. **40**, no. 7, pp. 987-994, 2008.