Multi-objective optimization of process parameters during friction stir welding of similar AA6061 using MOORA

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Abstract: *This work is an attempt to select the optimum process parameters for friction stir welding of similar AA6061 aluminum alloy based on multiple criteria decision-making approach. The friction stir welding experiments have been conducted according to the orthogonal L9 array and the chosen input parameters are tool rotational speed, feed, and tilt angle. The responses measured are tensile strength, hardness, and % of elongation of welded joint. The multi-criteria decision-making technique namely multi-objective optimization based on the ratio analysis (MOORA) is used to find the optimum process parameters combination. The optimum conditions are tool rotational speed of 1120 rpm, feed of 30 mm/rev and tilt angle at 1°.*

Key Words: *Friction stir welding, Tensile strength, Hardness, MOORA, ANOVA*

1. INTRODUCTION

In the welding of high-strength lightweight materials like aluminum alloys, which are widely used in shipbuilding, aircraft, automotive, and structural applications, FSW plays a significant role. It prevents issues with the fusion welding process that are common with solidification cracking, distortion, and porosity [1]. Greater productivity, lower energy use, greater tensile and fatigue strength with less shrinkage are all benefits of FSW [2].

Srujan Manohar and Karunanithi Mahadevan [3] performed the optimization of multi-responses for micro-friction stir welded Al6061-T6 and SS304 sheets using TOPSIS. The results revealed that the ultimate-tensile strength, micro-hardness, and surface-roughness are greatly influenced by the tool-rotational speed and tool-traverse speed. Ravi Sankar et al. [4] carried out multi-objective optimization of process parameters during FSW of dissimilar AA5083-AA6061 alloys using hybrid GRA and PCA. The results reported that tilt angle played vital role in affecting the responses, followed by feed and tool rotational speed.

Marichamy and Babu [5] determined the optimum process parameters using the Additive Ratio Assessment (ARAS) method during FSW of aluminum alloy A319. The optimal combination of process parameters was rotational speed of 700 rpm, welding feed of 40 mm/min and tool pin diameter of 6 mm. Sameer and Anil Kumar Birru [6] conducted FSW of dissimilar Dual Phase (DP) 600 Steel and aluminum alloy AA6082-T6. Technique for order of preference by similarity to ideal solution (TOPSIS) and Grey relational analysis (GRA) approaches were used to determine the optimal set of input parameters.

The optimal set of process parameters were tool rotational speed of 710 rpm, tool traverse speed of 32 mm/min, tool tilt angle of 0.5° and tool offset of 1.8 mm. Siva et al. [7] investigated the optimal process parameters in FSW of NAB alloy using multi-criteria decision making methods such as GRA and TOPSIS. The same combination of process parameters were obtained for both methods.

Sundar Singh Sivam et al. [8] used Grey relational analysis to determine the optimal conditions in FSW of dissimilar Ti (Grade 2) and Mg (AZ91D) Alloy. The results demonstrated that a rotation speed of 2000 Rpm, Travel speed of 210 mm/min, Bottom diameter of tool radius of 6 mm and tool design cylindrical are the most optimum conditions. Umamaheswarrao [9] optimized process parameters during friction stir welding of AA6061-AA7075 using desirability function analysis.

Using TOPSIS, Umamaheswarrao [10] optimized the process parameters during the friction stir welding of the alloys AA2014-AA7075. Using the response surface method coupled with GRA and PCA, Ravi Sankar and Umamaheswarrao [11] optimized process parameters during friction stir welding of AA 6061.

Ravi Sankar and Umamaheswarrao [12] studied and optimized the friction stir welding of AA 6061 using the response surface method. It was discovered that joints with lower speeds had superior tensile strength; as speed rises, the joint's hardness initially rises and subsequently falls. Vijaypraveen et al. [13] optimized LBM process parameters using MOORA method.

Moreover, a systematic study on the effect of tool rotational speed, feed and tilt angle in similar welds of AA6061 was not carried out. Hence the present work is aimed to determine the optimal welding parameters using MOORA.

2. EXPERIMENTAL DETAILS

A square butt joint configuration (100×75×6 mm) was prepared to fabricate FSW joints. A vertical milling machine made by HMT was used to fabricate the joints. The experimental setup is shown in Fig. 1. Chemical composition of AA6061 is presented in Table 1. The non-consumable tool made of H13 steel was used to fabricate the joints.

Table 2 shows the tool specifications. Nine joints were fabricated as per the condition dictated by the design matrix. Process parameters and their levels are shown in Table 3. Tensile test specimens are shown in Fig. 2

Table 1. Chemical composition of AA6061

Alloy	Chemical composition (wt%)							
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
AA6061	0.62	0.33	0.28	0.06	0.9	0.17	0.02	Bal.

Table 2. Tool specifications

Tool material	H13
Pin type	Cylindrical
Pin diameter	6 mm
Shoulder diameter	20.5 mm
Pin length	4.5 mm

Three parameters such as tool rotational speed, feed and tilt angle are varied at three levels throughout friction stir welding, and their influences on responses such as tensile strength, hardness and % elongation are examined.

To reduce both time and expense, the experimental runs are created in accordance with Taguchi's L9 orthogonal array. The experimental results are shown in Table 4. The hardness test specimens are shown in Fig. 3.

Fig. 1 Experimental setup [10]

Fig. 2 Specimens after tensile test

Table 3. Process parameters and their levels

Parameter	Symbol	Level 1	Level 2	Level 3
Tool rotational speed (rpm)	A	710	900	1120
Feed (mm/rev)	B	30	40	50
Tilt Angle (°)	C	0	1	2

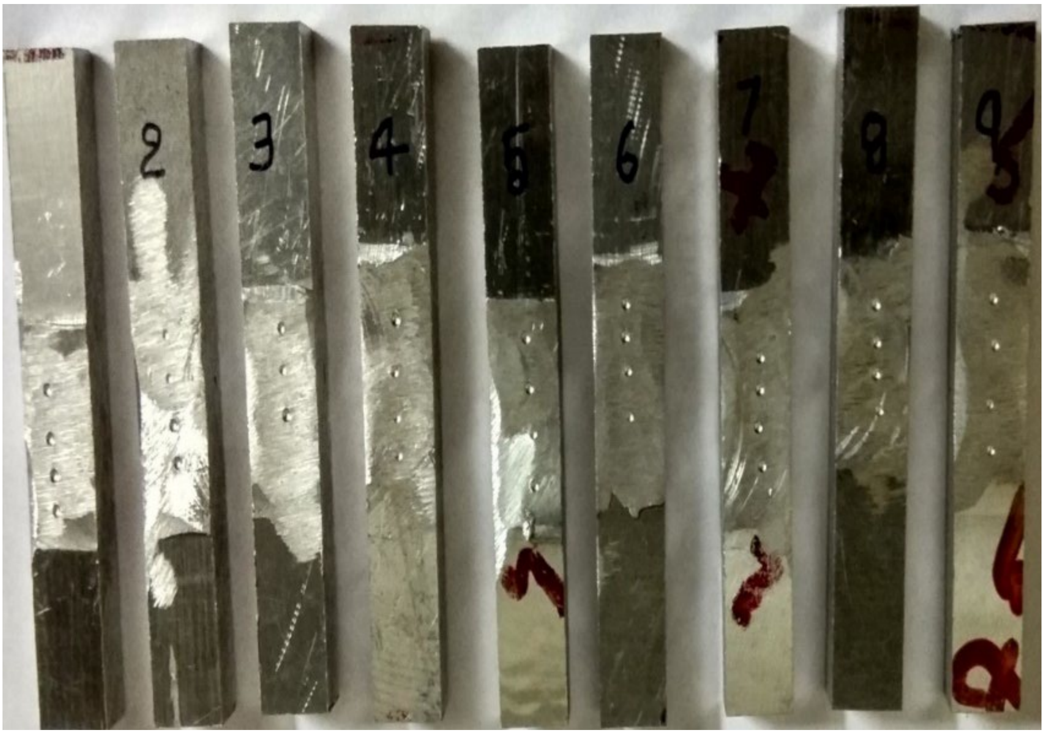

Fig. 3 Hardness test specimens

Table 4. Experimental results

Expt. No	Tool rotational speed (rpm)	Feed (mm/rev)	Tilt angle (°)	Tensile strength (MPa)	Hardness (BHN)	% Elongation
1	710	30	0	125.93	80.67	5.2
2	710	40	1	182.328	83.67	12.88
3	710	50	2	142.337	86.67	4.82
4	900	30	1	181.08	86.33	13.78
5	900	40	2	164.769	85.67	7.56
6	900	50	0	143.215	91	5.82
7	1120	30	2	176.98	83	11.78
8	1120	40	0	144.410	84.67	5.68
9	1120	50	1	184.788	90	10.48

3. METHODOLOGY

Multi-objective optimization on the basis of ratio analysis (MOORA)

The technique of simultaneously maximizing two or more competing attributes (objectives) within specified restrictions is referred to as multi-objective optimization (or programming). It is also known as multi-criteria optimization or multi-attribute optimization.

One such multi-objective optimization method that can be successfully used to address various sorts of complicated decision-making issues in the manufacturing environment is the MOORA method, which was first described by Brauers [14].

The MOORA technique [15-21] begins with a decision matrix that displays how several alternatives perform in relation to certain criteria (objectives).

The multi-objective optimization on the basis of MOORA method starts with a decision matrix as shown in equation:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

where x_{ij} is the performance measure of i^{th} alternative on j^{th} attribute, m is the number of alternatives, and n is the number of attributes.

Step 1: Compute the normalized decision matrix by vector method defined by equation:

$$X_{ij}^{a} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^{2}}} \quad i = 1, 2, 3, \dots, m; \; j =, 2, 3, \dots, n \tag{2}$$

where x_{ij} is a dimensionless number which belongs to the interval [0, 1] representing the normalized performance of i^{th} alternative on j^{th} attribute.

For multi-objective optimization, these normalized performances are added in case of maximization (for beneficial attributes) and subtracted in case of minimization (for non-beneficial attributes).

Then the optimization problem becomes

$$Z_i = \sum_{j=1}^{b} X_{ij}^{a} - \sum_{j=g+1}^{n} X_{ij}^{a} \tag{3}$$

where g is the number of attributes to be maximized, (n-g) is the number of attributes to be minimized, and Z_i is the normalized assessment value of i^{th} alternative with respect to all the attributes.

Where $\sum_{j=1}^{b} X_{ij}^{a}$ and $\sum_{j=g+1}^{n} X_{ij}^{a}$are the benefit and non-benefit criteria respectively.

In order to give more importance to an attribute, it could be multiplied with its corresponding weight (significance coefficient) [17]. When these attribute weights are taken into consideration, Eq. (3) becomes as follows

$$Z_i = \sum_{j=1}^{b} w_j X_{ij}^{a} - \sum_{j=g+1}^{n} w_j X_{ij}^{a} \quad i = 1, \; m \tag{4}$$

where w_j is the weight of j^{th} attribute, which can be calculated using the entropy method or analytic hierarchy process.

Depending on the decision matrix's totals for the maxima (beneficial attributes) and minima (non-beneficial attributes), the Z_i value can be either positive or negative. An ordinal ranking of Z_i shows the final preference.

Since the worst alternative has the lowest Z_i value, the best alternative has the highest Z_i value.

Table 5. Normalized values for UTS, Hardness and % Elongation

Expt. No	Normalized UTS	Normalized Hardness	Normalized % Elongation
1	0.25914	0.3134116	0.1864359
2	0.37521	0.3250669	0.4617874
3	0.29291	0.3367222	0.1728117
4	0.37264	0.3354013	0.4940552
5	0.33907	0.3328371	0.2710491
6	0.29472	0.3535447	0.2086648
7	0.36420	0.3224639	0.4223490
8	0.29717	0.3289520	0.2036454
9	0.38027	0.3496596	0.3757401

4. RESULTS AND DISCUSSIONS

Table 6. Overall assessment value and rank

Expt. No	Weighted normalized UTS	Weighted normalized Hardness	Weighted normalized % Elongation	Overall Assessment Value	Rank
1	0.0855192	0.1034258	0.0615238	0.2504689	9
2	0.1238192	0.1072720	0.1523898	0.3834812	2
3	0.0966613	0.1111183	0.0570278	0.2648075	8
4	0.1229717	0.1106824	0.1630382	0.3966924	1
5	0.1118949	0.1098362	0.0894462	0.3111774	5
6	0.0972575	0.1166697	0.0688593	0.2827867	6
7	0.1201874	0.1064130	0.1393752	0.3659757	3
8	0.0980690	0.1085541	0.0672029	0.2738262	7
9	0.1254898	0.1153876	0.1239942	0.3648717	4

A higher value of overall assessment value indicates better performance. From Table 6, it is evident that experiment no. 4 accomplished the highest value of overall assessment value among the 9 experiments and the optimum condition to achieve the multiple performance characteristics (tool rotational speed = 1120 rpm, feed = 30 mm/rev, and tilt angle = 1^o)

ANOVA was used to estimate the percentage contribution of each process parameters on multi-objective optimization.

From the ANOVA analysis, it is clear that tilt angle (75.69%) contribution is the maximum afterward tool rotational speed (8.65%) and feed (6.65%) as depicted in Table 7. Fig. 4 illustrates the main effect plot for the overall assessment value. This graph is used to determine the optimum parameter combination.

The peak value at each level of the Fig. 3 represents the optimal result for overall assessment value i.e. A3 (Tool rotational speed at 1120 rpm), B1 (Feed at 30 mm/rev), C2 (Tilt angle at 1^o) and the same was observed from the mean response table for the closeness coefficient shown in Table 8. Overall assessment value decreases with an increase in feed. With an increase in tool rotational speed from 700 rpm to 900 rpm overall assessment value surges. Fig. 5. shows Expt. No Vs Overall assessment value

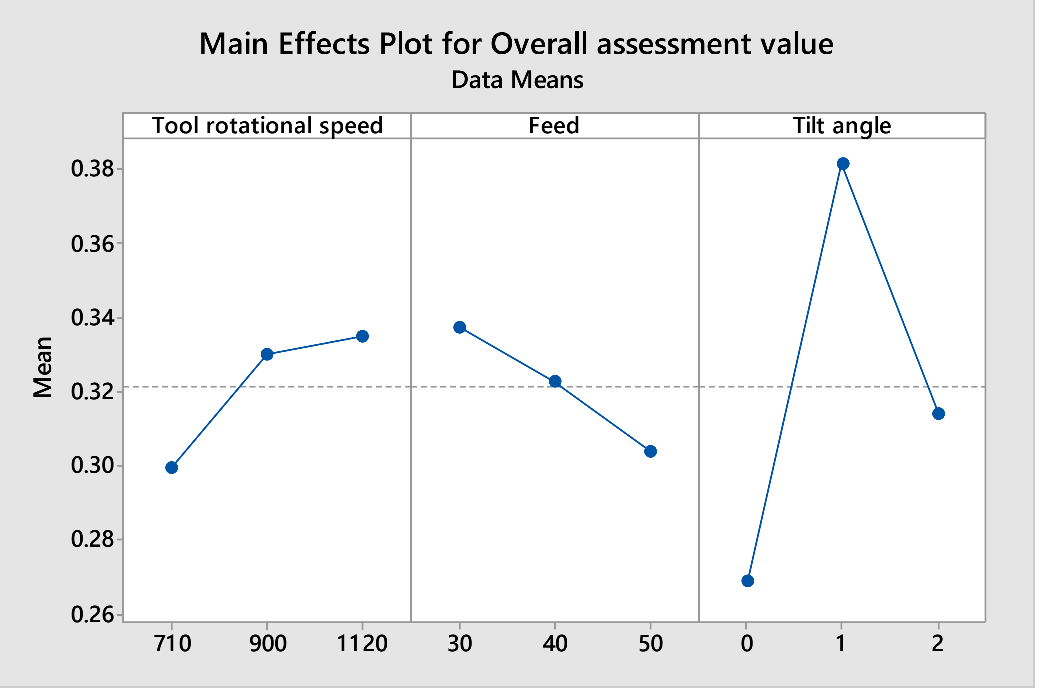

Fig. 4 Main effects plot for overall assessment value

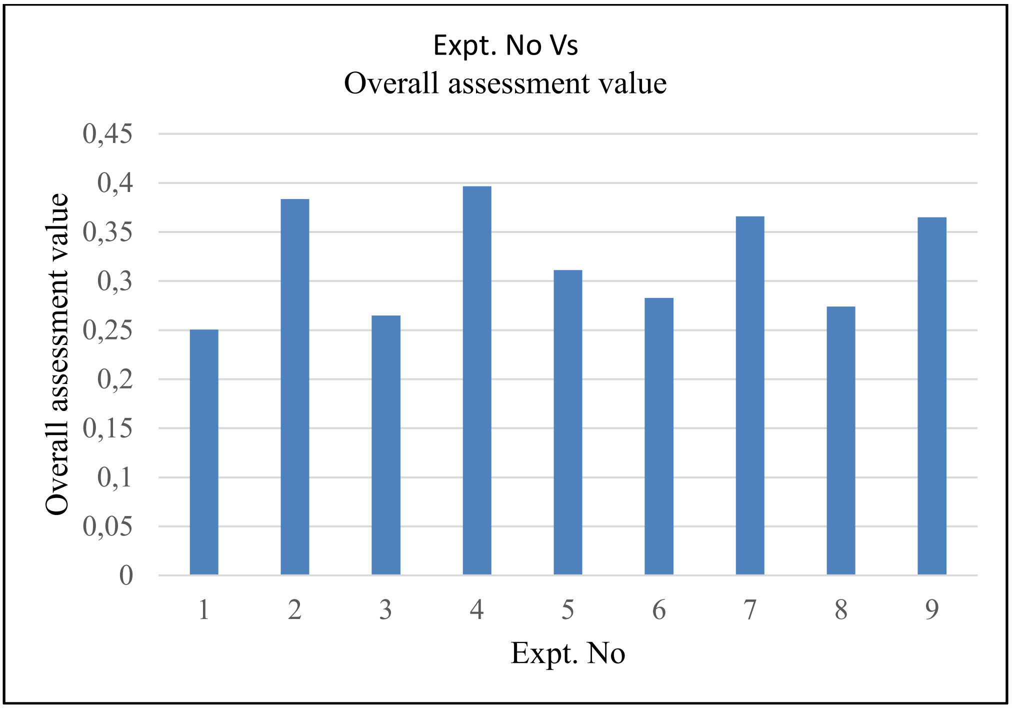

Fig. 5 Expt. No Vs Overall assessment value

Table 7. ANOVA for overall assessment value

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Tool rotational speed	2	0.002207	0.001103	0.96	0.510	8.65
Feed	2	0.001696	0.000848	0.74	0.575	6.65
Tilt angle	2	0.019295	0.009647	8.41	0.106	75.69
Error	2	0.002294	0.001147			
Total	8	0.025492				

S= 0.0338694, R-sq = 91.00%, R-sq(adj)= 64.00%

Table 8. Response table for means of overall assessment value

Level	Tool rotational speed	Feed	Tilt angle
1	0.2996	**0.3377**	0.2690
2	0.3302	0.3228	**0.3817**
3	**0.3349**	0.3042	0.3140
Delta	0.0353	0.0336	0.1127
Rank	2	3	1

In the mean response table (Table 8) tilt angle is allocated a rank 1 which means it is the most important parameter in controlling the response followed by tool rotational speed and feed.

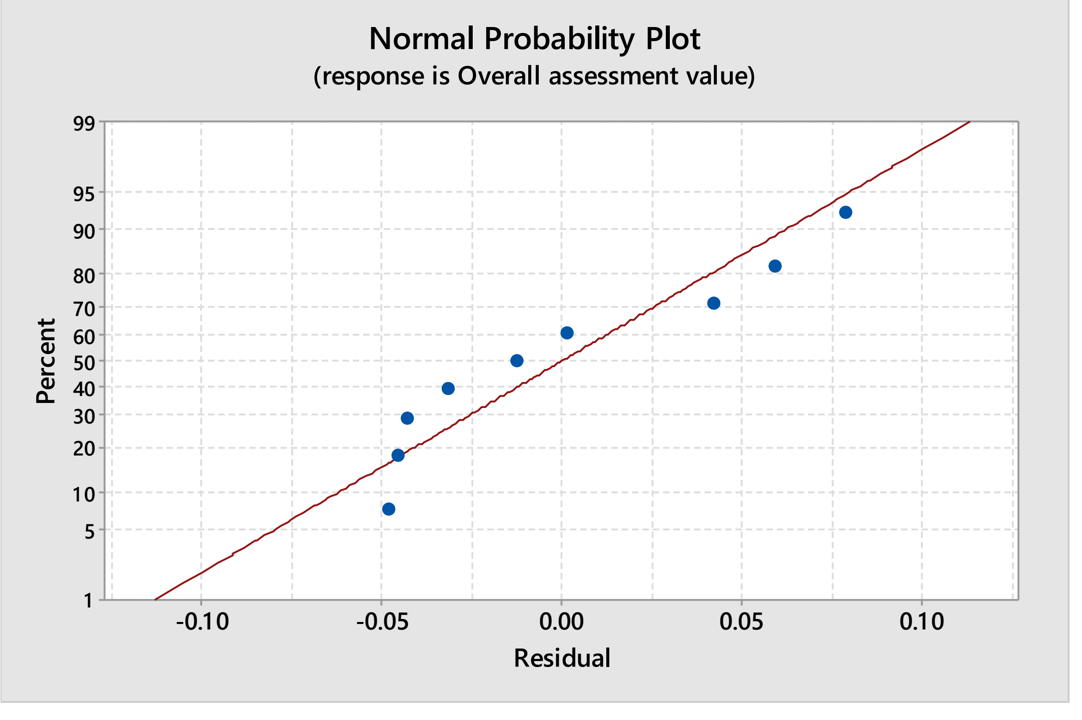

Fig. 6 Normal probability value for overall assessment value

Residuals for overall assessment value indicate that they lie fairly close to the straight line as shown in Fig. 6.

The regression equation for overall assessment value is given in equation 5. Regression coefficients are presented in Table 9.

Table 9. Regression coefficients

Term	Coef	SE Coef	T-Value	P-Value
Constant	0.289	0.154	1.88	0.118
Tool rotational speed	0.000084	0.000123	0.69	0.522
Feed	-0.00168	0.00251	-0.67	0.534
Tilt angle	0.0225	0.0251	0.89	0.412

$$\text{Overall assessment value} = 0.289 + 0.000084 \times \text{Tool rotational speed} - 0.00168 \times \text{Feed} + 0.0225 \times \text{Tilt angle} \tag{5}$$

From Table 6, it is evident that experiment number 4 was the better performer. The order of the experimental run obtained by MOORA was given as 4-2-7-9-5-6-8-3-1.

The overall assessment value for the obtained optimum combination of parameters was 0.41117 appraised from eq. 6 and was 3.6% greater than the maximum overall assessment value corresponding to rank 1 in Table 6.

Hence the values obtained were optimum. Significant interaction was observed between tool rotational speed and feed as depicted in Fig. 7.

$$\gamma = \gamma_m + \sum_{j=1}^{bq} (\overline{\gamma_j} - \gamma_m) \tag{6}$$

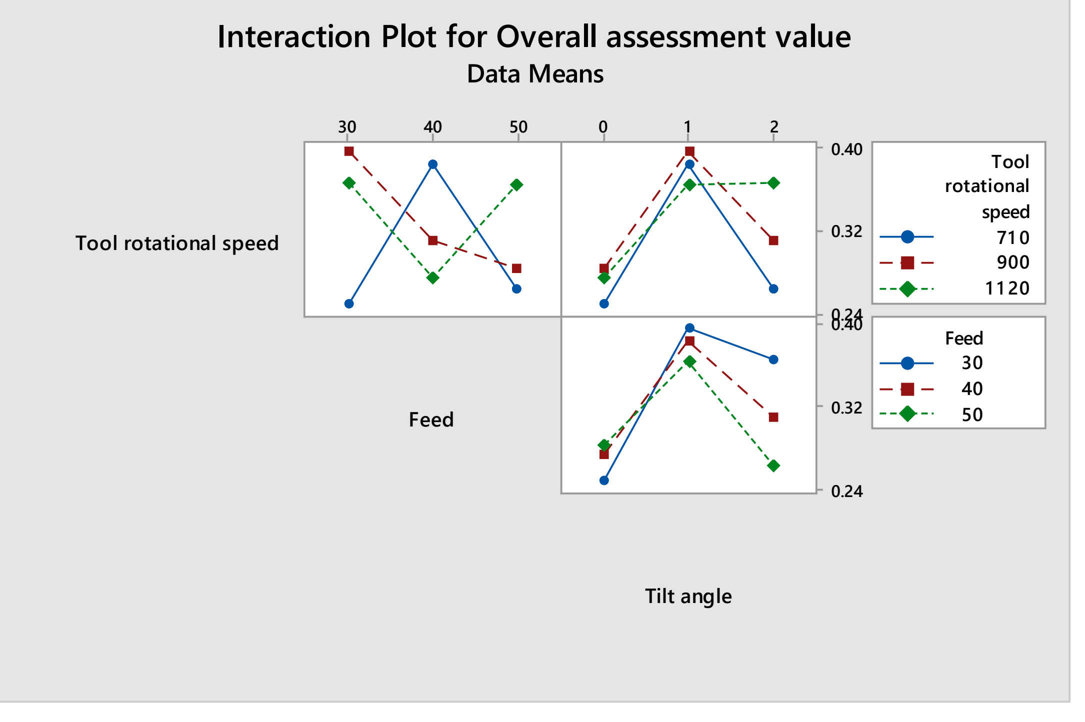

Fig. 7 Interaction plot for overall assessment value

5. CONCLUSIONS

The optimization of parameters with multiple performance characteristics (Tensile strength, Hardness and % Elongation) during FSW of similar AA6061-AA6061 was carried out. The experiments were conducted as per the L_9 orthogonal array and the multi-objective optimization was achieved through MOORA. The following conclusions were drawn from this study:

- Tilt angle was observed to be the most significant factor affecting the responses followed by tool rotational speed and feed.
- It is clear from the results of MOORA that experiment no. 4 has the highest overall assessment value. The obtained optimum combinations of parameters are i.e. tool rotational speed-1120 rpm, feed rate-30 mm/rev, and tilt angle-1°.
- From the ANOVA, the tilt angle (75.69%) has a significant influence followed by tool rotational speed (8.65%) and by feed (6.65%) which has the least influence
- From the values of overall assessment value, the FSW parameters best combination can be arranged in the order 4-2-7-9-5-6-8-3-1.
- The results obtained were in good agreement with ANOVA

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