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ORIGNAL ARTICLE

Optimization of processing parameters and output responses of friction stir welded joint of AA2014 and AA7075 by response surface methodology

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Abstract

The present study was designed to optimize the processing parameters of FSWed joint of dissimilar Al-alloys of AA2014 and AA7075. The FSW of Al-alloys of AA2014 and AA7075 of 6.2 mm plates have been welded successfully. The experiments were designed with the help of CCD of RSM, and the input parameters i.e. Tool rotational speed, traverse speed, and tool tilt angle were opted. Maximum tensile strength (279 MPa) was observed at TRS of 1400 rpm, TS of 70 mm/min with TTA 2^0, and the minimum tensile strength (162 MPa) was found at TRS of 1100 rpm, TS 40 mm/min with TTA 2^0. The maximum hardness (111 HV) was observed at TRS of 1400 rpm, TS 55 mm/min with TTA 1^0, and the minimum micro-hardness (66 HV) was found at tool rotation speed 1100 rpm, TS 40 mm/min with TTA 1^0. Empirical correlation was developed between input and output responses and observed optimized value of tensile strength, % strain and hardness at SZ were 174.62 MPa, 15.57, and 71.19 HV respectively. In contrast, the optimized value of TRS, feed rate, and TTA were observed as 1152.44 rpm, 41.05 mm/min, and 1.585. The fine and equiaxed grains structure in the SZ was observed at TRS of 1400 rpm, TS of 70 mm/min and TTA of 2º.

1. Introduction

Friction stir welding (FSW) is a joining process with a solid-state nature that uses a non- consumable metal tool to join two components. In this process, there is no need to make the workpieces melt and the heat is supplied by the friction behavior between the tool and work pieces. Both rotating and pressure are applied to the weld line by the tool to make the region softer and then to mix the material and forge them together [1–3]. Many researchers worked on welding of different metals and their alloys by the friction stir and reported their findings. One of the investigations is carried with the effective use of response surface methodology central composite experimental design to prepare AA 6061-T4 aluminium alloy friction stir welded specimens. The process parameters are considered for the welding are axial force, rotational speed and weld travel speed. The experimental model is developed to predict tensile strength of the weld joint and optimum condition is mentioned as 78 mm/min rotational speed, 7.2 kN axial force at 95% confidence limit [4]. Aluminium alloys grades, AA2014 and AA6061 is attempted to friction weld and effect of various process parameters on mechanical properties are experimental investigated. Response surface technique is used to design and analyze the effects of process parameters on mechanical properties statistically [5]. From the above literature reviews, it is observed that very few research works have been carried out in dissimilar FS welding of aluminium alloys and those researches have not studied the

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dissimilar FS welding of AA6351 and AA5083 which is widely used in aerospace, shipbuilding and other fabrication industries with the help of response surface methodology (RSM). RSM is helpful in developing a suitable ballpark figure for the well-designed relationship between the independent variables and the response variable that may exemplify the nature of the joints. These have been proved by several researchers already [6-10]. The higher welding speeds were associated with low heat inputs and resulted in faster cooling rates of the welded joint. The microstructural evolution of dissimilar welds as a function of processing parameters has been widely studied to find the behavior of AA6061-AA2024 materials [11]. New welding approach has been introduced to improve the welding quality of TIG welded joint, the influence of friction stir processing on TIG welded joint have been analyzed and they observed that mechanical properties and heat transfer of TIG+FSP welded joint [12-18]. Deepak Chouhan et al., [19] observed the effect of rotational speed, welding speed and three different pin profiles on the stir zone evolution in AA6063-T4 Aluminium alloy and the tensile behavior of the welded joints have been discussed. The optimization of process parameters of friction stir welding of cast Aluminium alloy A319 using Taguchi method obtained by Jayaraman M et al., [20] and found that the tool rotational speed was the predominant parameter for tensile strength followed by welding speed. Rajakumar S, et al., [21] focused the development of empirical relationship for the tensile strength of friction stir welded AA1100 aluminium alloy joints and observed that the rotational speed was more sensitive than the welding speed. Nicole Adler et al., [22] revealed that the statistical techniques have been used to quantify the relative efficiency of decision-making units with multiple inputs and outputs. Chih-Wei Tsai et al., [23] tried to optimize the responses using data envelopment analysis with response surface methodology. In this existing work an attempt has been carried out to optimize the process parameters on the multiple responses of Impact strength and Vickers hardness for friction stir welded AA8011 Aluminium alloys based on L9 orthogonal array with data envelopment analysis based Taguchi method.

In this work, the different phenomena (Optimization and mechanical properties) during welding of AA2014 and AA7075 plates using the FSW technique was studied. The objective of this experimental work is to optimize the input parameters i.e. tool rotational speed, traverse speed, and tool tilt angle for obtaining the highest and optimized value of output responses i.e., tensile strength, strain, and hardness of the FSWed joint of AA2014 and AA7075. These experiments were developed by design expert software, and mathematical model was also developed by response surface methodology.

2. Materials and Method

In this work, the experimental work was conducted on dissimilar aluminium alloy plates of 6 mm thickness. The dissimilar aluminium AA2014, and AA7075 were friction stir welded to fabricate the joint. The chemical composition of the parent materials was mentioned in Table 1.

Table 1: Chemical composition of AA2014 and AA7075

Material	Si	Cu	Fe	Zn	Mg	Mn	Cr	Al
AA 2014	0.85	4.2	0.6	0.25	0.6	1.2	0.1	Bal.
AA7075	0.58	1.2	0.35	5.1	1.2	0.8	0.16	Bal.

The experimental set up consists of a Friction Stir Welding machine. The FSW machine has a rigid base, tool head, table, rotating spindle, horizontal and automated process control which favours the FSW process as shown in fig. 1.

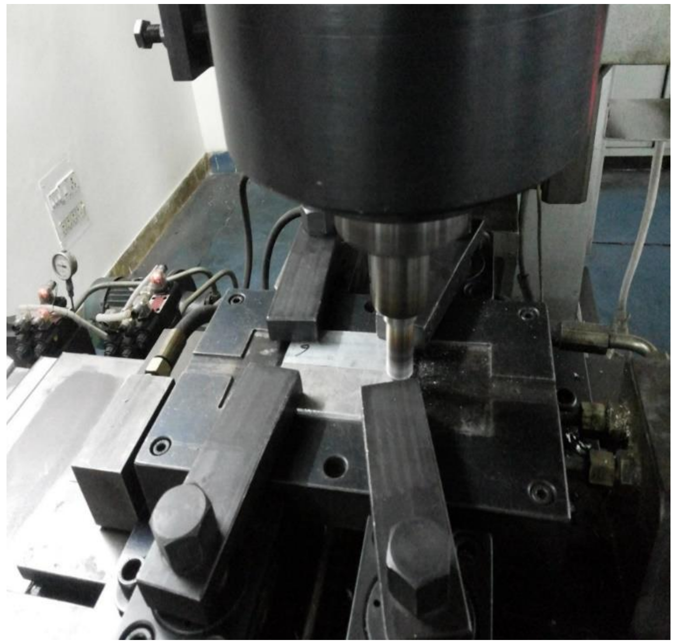


Figure 1: Friction stir welding machine

Single pass butt welding procedure was used to fabricate the dissimilar AA2014 and AA7075 FSW joints in the plates size of 120x40x6 mm. Specially designed fixture was used to firmly hold the workpiece against the axial force of rotating FSW tool. Friction stir welding process parameters, namely tool rotational speed, tool traverse speed and tool tilt angle has been taken for fabricating the dissimilar alloy joint. Tool rotational speed was taken in the range of 1100-1400 rpm, traverse speed range of 40-70 mm/min, and the tool tilt angle range of 0-2º. These FSW parameters were optimized to attain the maximum tensile strengths and microhardness of the weld joint. The FSW tool consists of threaded cylindrical pin shoulder diameter of 19.5 mm and pin length of 5.5 mm for welding the plate with 6mm thickness. The tool pin diameter was taken as 6 mm. H13 tool steel was used as tool material for its high strength, low cost, easily availability and easy to process.

In order to investigate the mechanical properties of the FSWed joints, transverse and longitudinal tensile tests and Vickers microhardness test along with the microstructure test were performed. Tensile test specimens were prepared according to the subsize sample of the ASTM E8 standard [24]. Transverse tensile test was carried out on universal testing machine. Thus, transverse tensile specimens were extracted from the FSWed samples so that the stir zone was placed at the center of the gage length. Longitudinal tensile test was performed for evaluation of the mechanical behavior of the stir zone, and given this purpose, longitudinal tensile specimens were cut from the center of the stir zone.

3. Results and Discussions

3.1 Tensile strength

The processing parameters i.e. tool rotational speed, tool traverse speed and tool tilt angle was selected by design expert software. Twenty experiments were done on the basis of input parameters. The output responses are shown in table. 2. The mechanical properties of FSWed joint of AA2014 and AA7075 were discussed in details below. Table 2 summarizes the values of tensile strength, % strain, microhardness of FSWed joint. It observed that the %strain, a tensile strength increased when TRS increases is shown in fig. 2. At the same TRS, the tensile strength decreases when TS increases. The value of tensile strength is lower than the base metal, but at TRS 1400 rpm, TS of 70 mm/min with TTA of 2º the value of tensile strength is closer to the parent metal. Based on the present results, it can be observed that there should be a trade-off between the hardness and the tensile strength although selecting the optimized input parameters.

When the TRS increases, the heat input also increases, due to this, a fine and equiaxed grain structure was observed which enhanced the tensile strength. When the TRS increases after 1400 rpm it may produce excessive heat on the top surface of the base plate, observed micro void in the SZ. The tensile strength of the welded joint of all twenty experiments were varies between 162-279 MPa. The minimum tensile strength of 162 MPa was found at TRS of 1100 rpm, TS of 40 mm/min with TTA of 2º is shown in fig. 2. The increase in temperature as well as coarsening of grains and cooling rate is more than the desired temperature may reduce the tensile strength of FSWed joint. Some defects were observed when material flow occurs on the A.S of the FSWed joint because no force promoting its movement back into the volume stirred by the rotating tool [25]. All the tensile test specimens were failed on TMAZ or HAZ region at advancing side. This will have happened because many coarse grain brittle structure were observed at TMAZ and HAZ region [26]. It was also observed that all joints were failed on the A.S, which shows that the tensile strength is different on both side of the weld center.

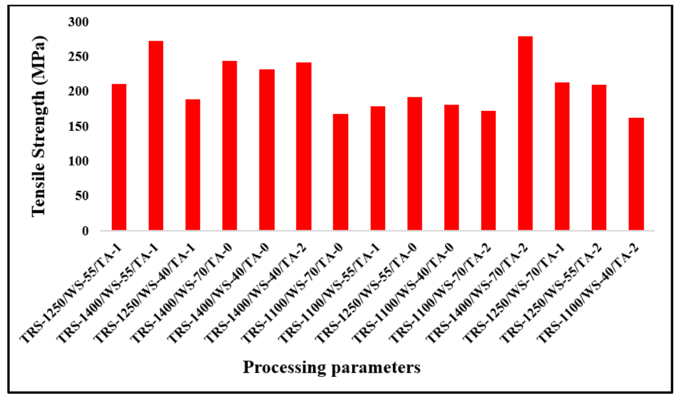


Figure 2: Variation of tensile strength to the processing parameters

Table 2: Input processing parameters and their responses

Sample No	A: Tool Rotational Speed (rpm)	B: Traverse Speed (mm/min)	C: Tilt Angle (degree)	Tensile Strength (MPa)	Strain (%)	Micro-hardness at SZ (HV)
1	1250	55	1	211	18.9	84
2	1400	55	1	272	24.6	111
3	1250	55	1	213	18.4	88
4	1250	55	1	209	18.7	84
5	1250	40	1	189	16.9	79
6	1400	70	0	244	22.2	98
7	1400	40	0	232	20.7	92
8	1400	40	2	242	21.6	97
9	1100	70	0	168	15	67
10	1100	55	1	179	16	76
11	1250	55	0	192	17	81
12	1100	40	0	181	16.2	72
13	1100	70	2	172	15.4	69
14	1400	70	2	279	25.2	108
15	1250	55	1	219	19.6	87
16	1250	70	1	213	19	80
17	1250	55	1	207	18.5	82
18	1250	55	1	205	18.3	88
19	1250	55	2	210	18.8	84
20	1100	40	2	162	14.5	66

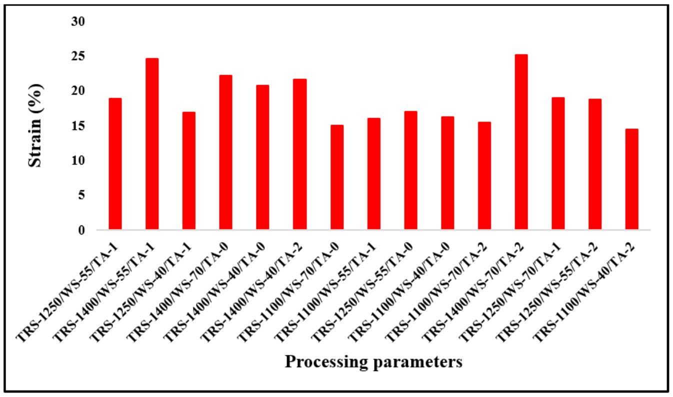


Figure 3: Variation of % strain to the process parameters

3.2 Micro-hardness at SZ

Fig. 4 shows the variation between hardness and processing parameters of the FSWed joint AA2014 and AA7075. However, the investigation of the micro-hardness across the weldment of AA2014 and AA7075 has been reported earlier [27]. The SZ of FSWed joint observed maximum hardness due to dissolution of the precipitation phase and fine recrystallized grain structure in that zone [28]. The hardness value is depending on the dislocation structure, grain size, and distribution of precipitates. The hardness value was decreasing from base metal to HAZ and TMAZ zone because these zones experiences coarse grain structure, making of aging precipitates, and insufficient temperature distribution.
The maximum hardness of 111 HV was found at TRS of 1400 rpm, TS of 55 mm/min with TTA of 1º, while the minimum hardness of 66 HV was found at processing parameters of TRS of 1100 rpm, TS of 40 mm/min with TTA of 2º.

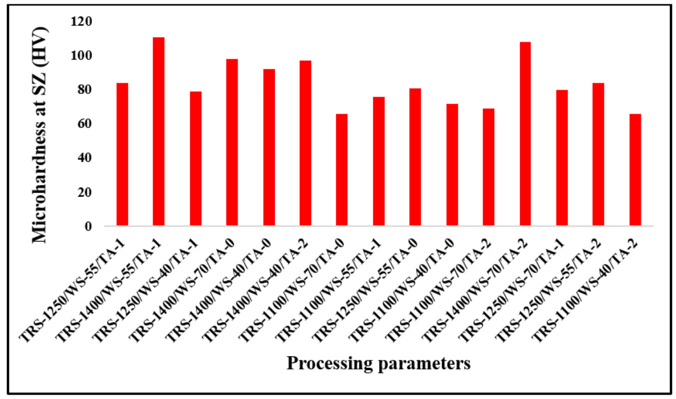


Figure 4: Variation of micro-hardness and processing parameters at Stir zone

3.3 Evaluating the adequacy of the developed model

The empirical correlation for the output responses developed, and the adequacy was analyzed by response surface methodology (RSM) technique. Twenty experiments were conducted which was design by design expert software. To analyzed the input and output responses which are statically significant or not, the ANOVA test was done by RSM technique, By ANOVA technique, we can have observed that which parameter will affect the mechanical properties of the FSWed joint of AA2014 and AA7075. After analyzing the ANOVA test, we can have concluded that the given process parameters are exceedingly important which affect the mechanical properties of the FSWed joint.

Table 3: ANOVA test results for tensile strength

Tensile strength						
Source	Sum of square	DOF	Mean square	F-Value	P-Value	
Model	19162.00	9	2129.11	66.34	< 0.0001	Significant
A-Tool Rotational Speed	16564.90	1	16564.90	516.13	< 0.0001	Significant
B-Traverse Speed	490.00	1	490.00	15.27	0.0029	Significant
C-Tilt Angle	230.40	1	230.40	7.18	0.0231	Significant
AB	338.00	1	338.00	10.53	0.0087	Significant
AC	450.00	1	450.00	14.02	0.0038	Significant
BC	288.00	1	288.00	8.97	0.0134	Significant
A^2	724.14	1	724.14	22.56	0.0007	Significant
B^2	188.20	1	188.20	5.86	0.0359	Significant
C^2	188.20	1	188.20	5.86	0.0359	Significant
Residual	320.95	10.00	32.09			
Lack of Fit	197.61	5.00	39.52	1.60	0.3087	not significant
Pure Error	123.33	5.00	24.67			
Cor Total	19482.95	19.00				

The ANOVA test results for output responses are shown in tables 3-5. All models have greatly significant Fisher's F value which reveals the adequacy of the developed model. The fisher's F value of 66.34 (table 3) was observed for developed model of tensile strength which reveals that the developed was significant, and only 0.01% error chance that a F-value of developed model could occurs due to noise. The fisher's F value for lack of fit was observed as 1.6 which shows that the lack of fit is not significant. The value of F should be not significant for the adequacy of the developed model. The value of residual error was observed as 320.95 that must be sum of value of pure error (123.33) and value of lack of fit (197.61).

Table 4: ANOVA test results for % strain

Strain (%)						
Source	Sum of square	DOF	Mean square	F-Value	P-Value	
Model	161.90	9	17.99	63.35	< 0.0001	Significant
A-Tool Rotational Speed	138.38	1	138.38	487.36	< 0.0001	Significant
B-Traverse Speed	4.76	1	4.76	16.77	0.0021	Significant
C-Tilt Angle	1.94	1	1.94	6.82	0.0253	Significant
AB	3.65	1	3.65	12.84	0.0049	Significant
AC	3.38	1	3.38	11.90	0.0062	Significant
BC	2.21	1	2.21	7.77	0.0192	Significant
A^2	7.28	1	7.28	25.65	0.0004	Significant
B^2	1.44	1	1.44	5.06	0.04824	Significant
C^2	1.64	1	1.64	5.78	0.03701	Significant
Residual	2.84	10.00	0.28			
Lack of Fit	1.71	5.00	0.34	1.51	0.3322	Not significant
Pure Error	1.13	5.00	0.23			
Cor Total	164.74	19.00				

Table 5: ANOVA test for micro-hardness at SZ

Hardness						
Source	Sum of Squares	DOF	Mean Square	F-value	p-value	
Model	2858.26	9	317.58	71.31	< 0.0001	Significant
A-Tool Rotational Speed	2464.90	1	2464.90	553.46	< 0.0001	Significant
B-Traverse Speed	22.50	1	22.50	5.05	0.04837	Significant
C-Tilt Angle	22.50	1	22.50	5.05	0.04837	Significant
AB	50.00	1	50.00	11.23	0.0073	Significant
AC	40.50	1	40.50	9.09	0.0129	Significant
BC	24.50	1	24.50	5.50	0.0409	Significant
A^2	160.36	1	160.36	36.01	0.0001	Significant
B^2	111.36	1	111.36	25.01	0.0005	Significant
C^2	31.11	1	31.11	6.99	0.0246	Significant
Residual	44.54	10	4.45			
Lack of Fit	13.04	5	2.61	0.41	0.8224	Not significant
Pure Error	31.50	5	6.30			
Cor Total	2902.80	19				

The fisher's F value of 63.35 was observed for developed model of % strain which reveals that the developed was significant, and only 0.01% error chance that a Fisher's value of developed model could occurs due to noise. The fisher's F value for lack of fit was observed as 1.51 which shows that the lack of fit is not significant. The value of F should be not significant for adequacy of the developed model. The value of residual error was observed as 2.84 that should be the sum of value of pure error (1.13) and value of lack of fit (1.71) as shown in table 4. The fisher's F value of 71.31 was observed for developed model of hardness which reveals that the developed was significant, and only 0.01% error chance that a Fisher's value of developed model could occurs due to noise. The fisher's F value for lack of fit was observed as 1.6 which shows that the lack of fit is not significant. The value of F should be not significant for adequacy of the developed model. The fit statistics data for various mechanical properties as shown in table 6.

3.4 Influence of input parameters on output responses

The RSM technique is used for optimization of process parameters and output responses using design expert software. The 3D response graph and contour plots are observed from the developed model by taking the optimized parameters. These figures reveals that the influence of input parameters on mechanical properties of FSWed joint of AA2014 and AA7075 as shown in fig. 5-6. The red color shows the high peak intensity, whereas blue color shows the low peak intensity.

Table 6: Fit Statistics data for various mechanical properties

Tensile Strength	Std. Dev.	5.6650	R^2	0.9835
	Mean	209.95	Adjusted R^2	0.9687
	C.V. %	2.6983	Predicted R^2	0.9139
			Adeq Precision	30.554
Strain (%)	Std. Dev.	0.53286	R^2	0.9827
	Mean	18.775	Adjusted R^2	0.9672
	C.V. %	2.8381	Predicted R^2	0.9110
			Adeq Precision	29.644
Micro-hardness	Std. Dev.	2.1103	R^2	0.9846
	Mean	84.6	Adjusted R^2	0.9708
	C.V. %	2.49452	Predicted R^2	0.9409
			Adeq Precision	28.900

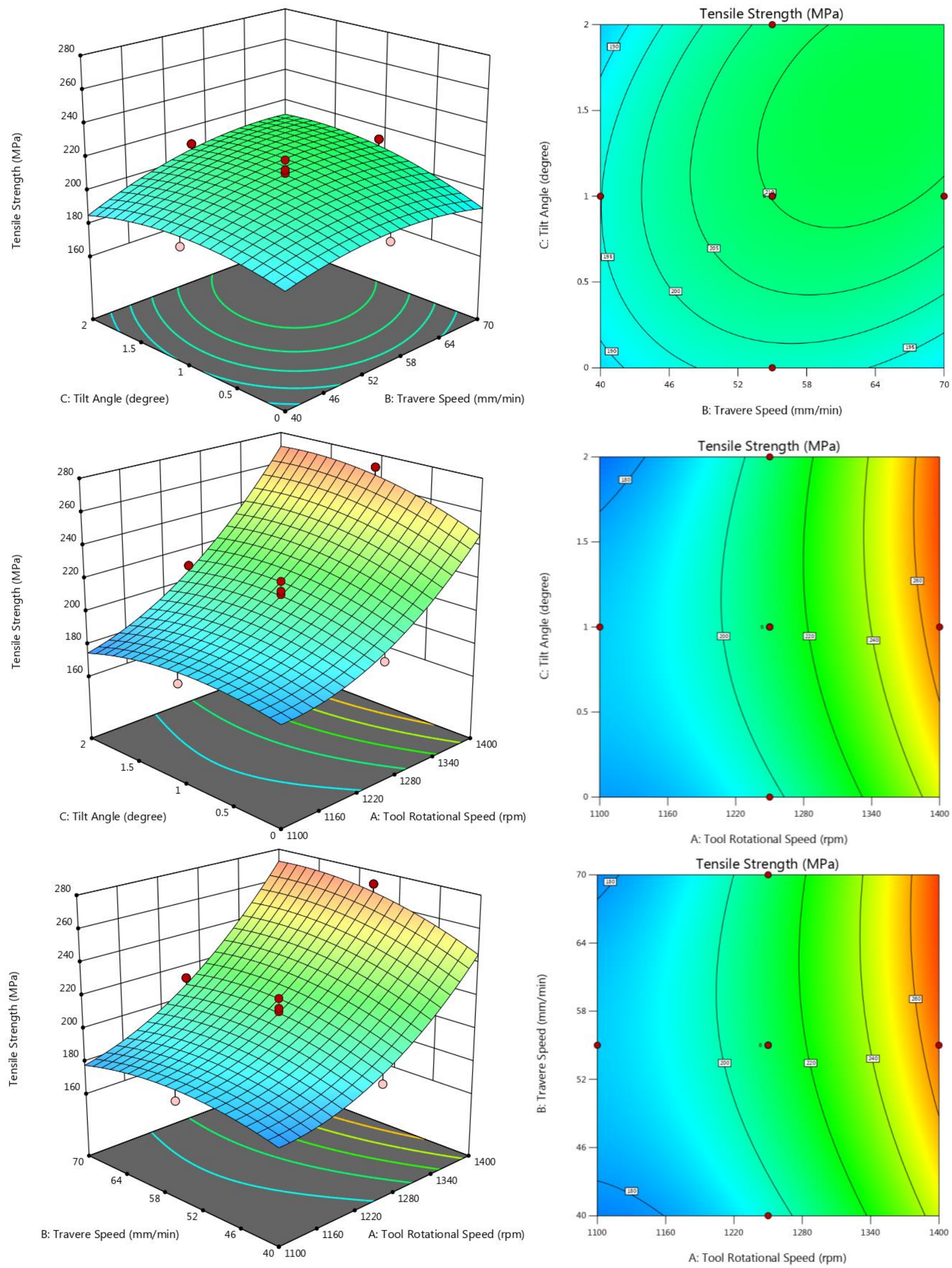


Figure 5: 3D response surface and contour plot for tensile strength

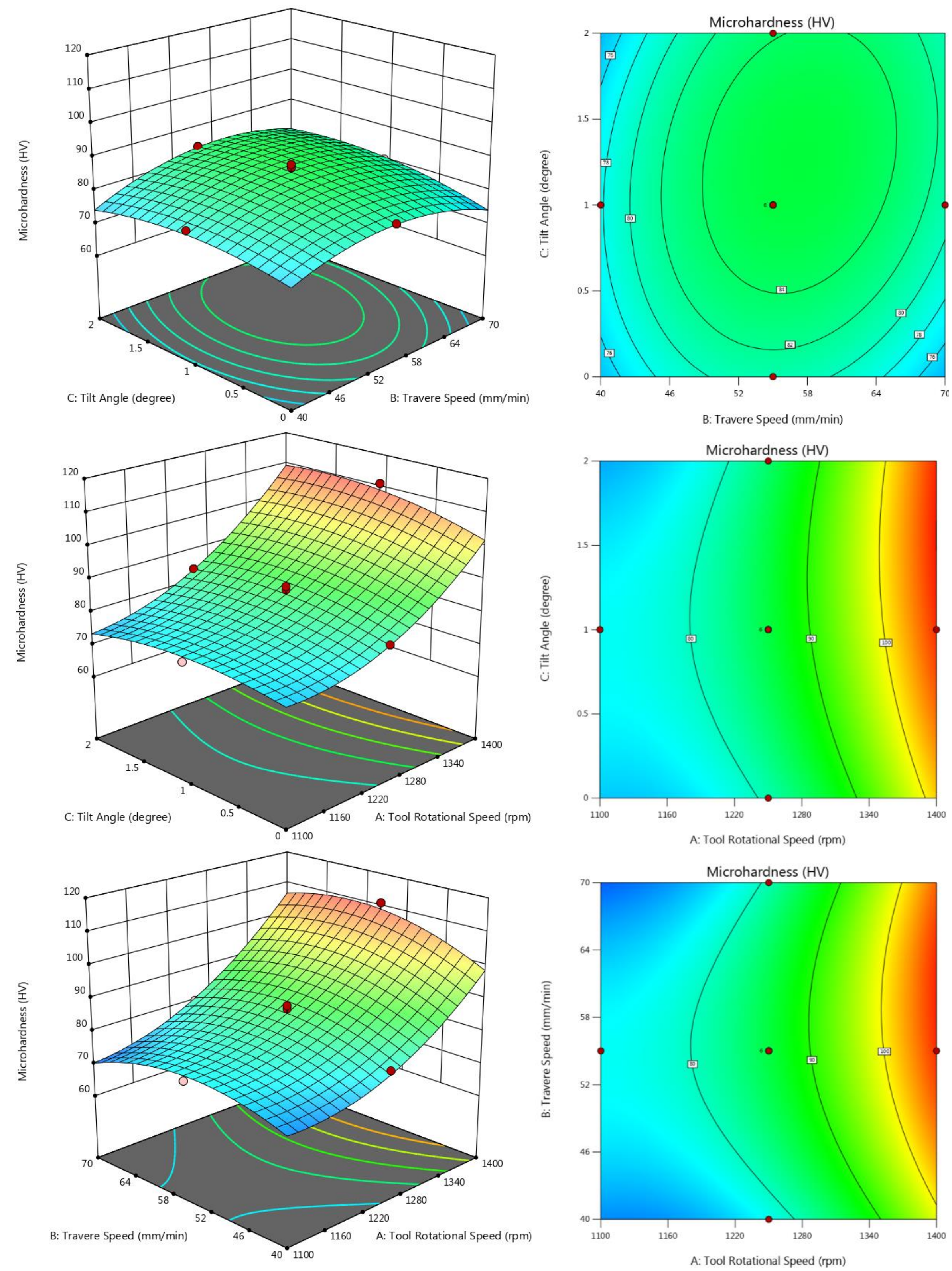


Figure 6: 3D response surface plot and contour plot for micro-hardness at SZ of FSW joint of AA2014 and AA7075

When the TRS increases, the tensile strength also increases, but as TS and TTA increases, the tensile strength first increases then decrease.
On the other hand, when the TRS increases, the % strain and hardness also increases, and when the TS and TTA increases, the % strain, hardness first increases then decrease as shown in fig. 5-6, because high heat generation was observed at high TRS and low TS [29]. heat generation.

3.5 Developing a mathematical model

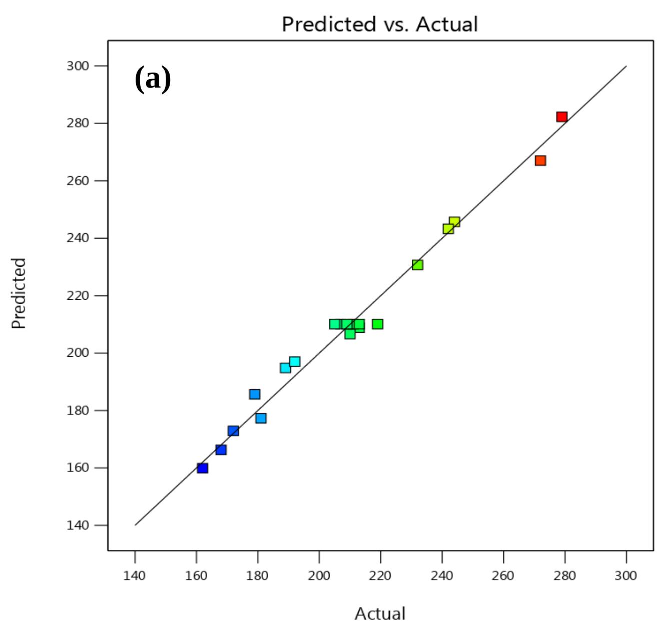
The empirical correlation is established for the output responses under the input variable given below

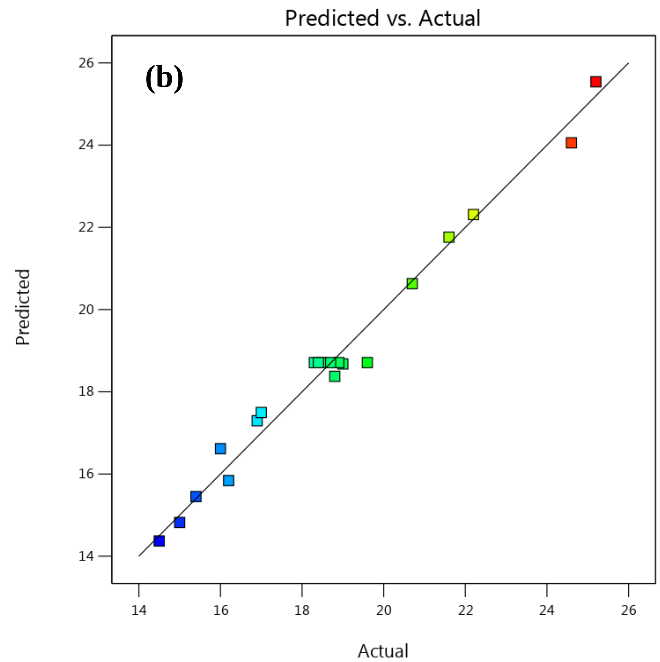
$$\text{Tensile strength} = 1130.99 - 1.74A + 0.5B - 63.15C + 0.0029AB + 0.05\,AC + 0.4\,BC + 0.0007A^2 - 0.0367\,B^2 - 8.127C^2$$

$$\text{Strain (\%)} = 115.22 - 0.1768A - 0.0106B - 5.356C + 0.0003AB + 0.0043AC + 0.035BC + 0.000072A^2 - 0.0032B^2 - 0.772C^2$$

$$\text{Micro-hardness} = 490.75 - 0.8199A + 1.705B - 16.939C + 0.0011AB + 0.015BC + 0.1167AC + 0.000339A^2 - 0.0282B^2 - 3.363C^2$$

Fig. 7 reveals the variation between the predicted value and actual value for output responses and it shows the prediction capabilities of the developed model. The errors were unvarying distributed throughout the model, if the points lying on a 45º straight line which was very closed to the actual values. Fig. 7 reveals a good correlation of predicted value and the actual values of the developed model.





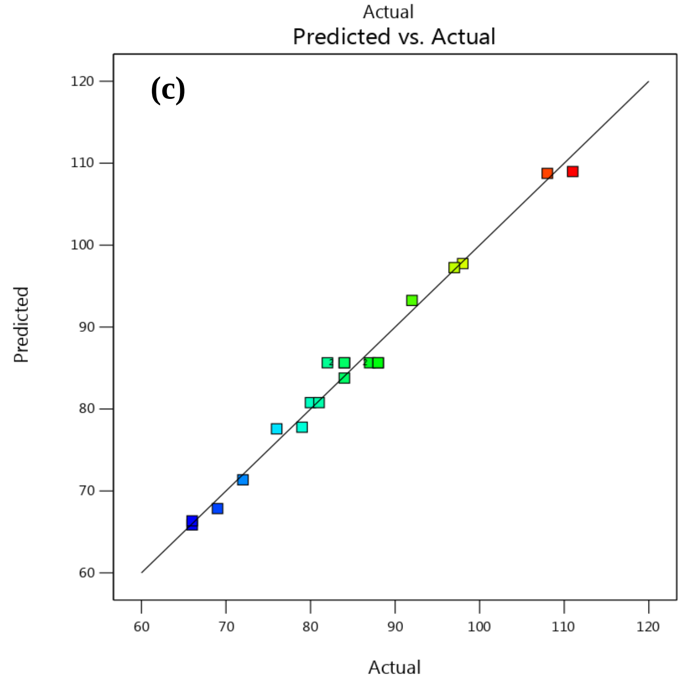


Figure 7: Predicted vs Actual Scatter diagram, (a) Tensile strength, (b) % strain, (c) Micro-hardness

Fig. 8 reveals the multi-response optimization results. This method is used for optimized for more than one objective function. The optimized value of tensile strength, %strain and hardness at the SZ were 174.62 MPa, 15.57 %, and 71.19 HV respectively, whereas the optimized value of TRS, feed rate and TTA are 1152 rpm, 41.05 mm/min and 1.585º respectively.

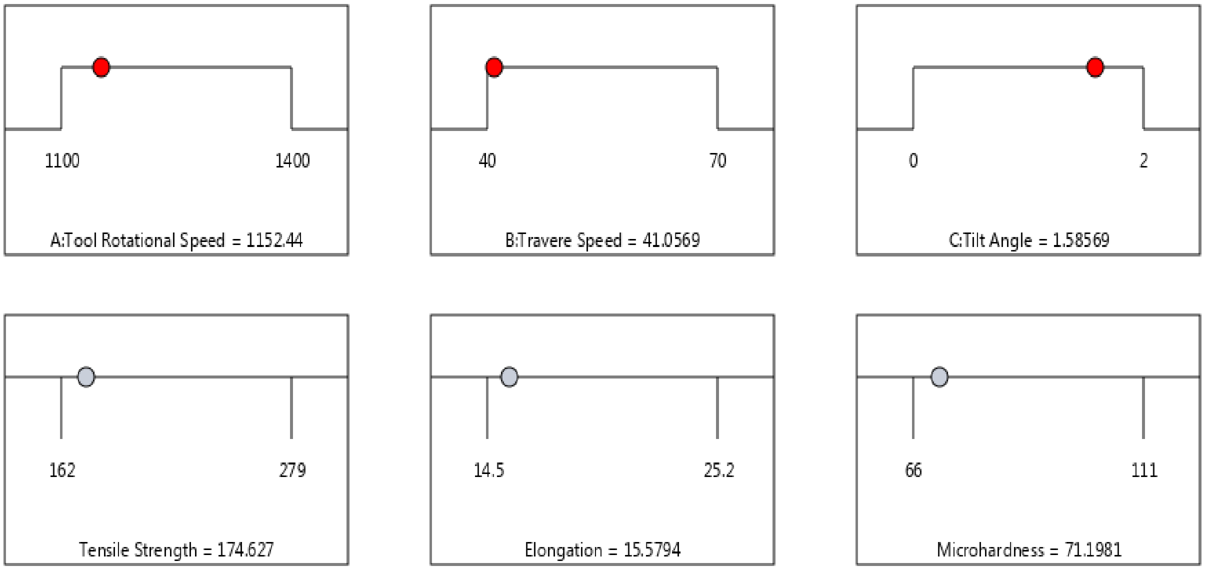


Figure 8: Ramp chart with optimized FSW parameters for output responses

4. Conclusions

The present study was designed to optimize the processing parameters of FSWed joint of dissimilar Al-alloys of AA2014 and AA7075, and the following conclusions have been made.

- The FSW of Al-alloys of AA2014 and AA7075 of 6.2 mm plates have been welded successfully.
- The experiments were designed with the help of CCD of RSM, and the input parameters i.e. TRS, TS, and TTA were opted.
- Maximum tensile strength (279 MPa) was found at TRS of 1400 rpm, TS of 70 mm/min with TTA 2^0, and the minimum tensile strength (162 MPa) was found at TRS of 1100 rpm, TS 40 mm/min with TTA 2^0.
- The maximum hardness (111 HV) was observed at TRS of 1400 rpm, TS 55 mm/min with TTA 1^0, and the minimum micro-hardness (66 HV) was found at tool rotation speed 1100 rpm, TS 40 mm/min with TTA 1^0.
- Empirical correlation was developed between input and output responses and observed optimized value of tensile strength, % strain and hardness at SZ were 174.62 MPa, 15.57, and 71.19 HV respectively. In contrast, the optimized value of TRS, feed rate, and TTA were observed as 1152.44 rpm, 41.05 mm/min, and 1.585.

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