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Experimental characteristics and optimization of friction stir welded AA5052-AA6061 using RSM technique

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ABSTRACT

Friction stir welding is a method that is normally used for aluminum alloys and is suitable for alloys which can be sensitive to heating during the welding manner. This mission used reaction floor technique to optimize manner parameters for friction stir welding of numerous aluminum alloys (Al 6061 and Al 5052). The effect of procedure parameters like rotational velocity, traverse velocity, and tilt angle on tensile energy and hardness has been studied. So as to improve productivity and weld excellent, optimized welding situations for max tensile strength and hardness have been predicted. The usage of layout professional software program, distinct aluminum plates have been welded by various parameters along with rotational pace, welding pace, and tilt perspective primarily based on RSM. The effects show that increasing the fee of RPM, feed fee, and device tilt attitude increases ultimate tensile electricity up to a certain point, after which it begins to lower. Joint energy is also exact at better tensile strength at 1100 rpm, 1–1.50 tool tilt attitude, and a minimum feed price of 28–30 mm/min.
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1. Introduction

Friction stir welding is a solid welding process that can weld hard materials using a fusion welding process. In addition, compared with the fusion welding process, this process is more energy efficient and environmentally friendly [1,2]. FSW is a stable nation joining process that entails the use of a non-consumable device to enroll in facing paintings pieces without melting the work piece cloth. Friction among the rotating tool and the work piece fabric generates warmness, resulting in a softened location close to the FSW tool [3]. Even as transferring alongside the joint line, the device automatically intermixes the two portions of steel and forges the new and softened metal by using applying mechanical strain [4]. It changed into generally used on wrought or extruded aluminum, and mainly for structures requiring extremely excessive weld energy [5]. Aluminum alloys, copper alloys, titanium alloys, moderate metal, stainless steel, and magnesium alloys can all be joined using FSW. It has these days been used correctly in polymer welding [6,7]. Moreover, FSW has currently done the joining of dissimilar metals together with aluminum to magnesium alloys [8]. While in comparison to fusion welding approaches, the application of the progressive and cutting-edge solid-state Friction Stir Welding (FSW) procedure gives many blessings in terms of procedure high quality, including no splash, no smoke, no gasoline, and no oxidation defensive [9]. At some stage in FSW experiments on multiple Al alloys—AA5052-O and AA6061-T6—Park and Kim investigated the effect of device rotation velocity and tool traverse pace on stirring action and friction warmness [10]. They used a ramification of process parameters to decide the mechanical strength of the diverse substances' weld nuggets [3]. They came to the realization that the satisfactory situations were a traveling pace of sixty one mm/min and a rotation pace of 1600 rpm. Their observations of the weld floor finish and plastic glide conduct discovered that because the traverse velocity turned into decreased, the stirring effect extended and the wide variety of defects decreased [11]. Table 1. shows the Chemical composition of AA6061-T6 and AA5052.

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Table 1
Chemical composition of AA6061-T6 and AA5052.

Material	AA6061	AA5052
Component	**%weight**	**%weight**
Al	95.85–98.56	95.6–95.7
Mg	0.8 – 1.2	2.2–2.8
Si	0.4 – 0.8	0.25
Cu	0.15 – 0.4	0.1
Fe	0.7	0.4
Cr	0.04–0.35	0.15–0.35
Ti	0.25	–
Mn	–	0.1
Zn	–	0.1

The impact of method parameters at the mechanical properties, which includes tensile strength and hardness of the fsw joint of varied aluminum alloys (Al5052 and Al6061), became studied on this have a look at, in addition to the micro structural adjustments [15]. The process parameters had been optimized in design expert software using RSM methodology.

2. Methodology

2.1. Experimentation

2.1.1. Material selection

The materials used in this check are AA 6061 and AA 5052, both of that are commercially available. Friction stir welded 4 mm thick AA 6061 and AA 5052 plates in numerous parameter combos the use of a pc numerically managed vertical milling machine and a in particular designed fixture [12]. The D/d ratio (shoulder/pin) became stored at 3, with the shoulder diameter at 18 mm and the pin diameter at 5 mm [13]. Fig.1 depicts the Methodology of Experiment.

2.1.2. Tool selection

H13 tool steel is a versatile chromium molybdenum steel that may be utilized in both hot and cold working applications [14-16]. Hard H13 resists thermal fatigue cracking in hot working tools due to cyclic heating and cooling cycles.

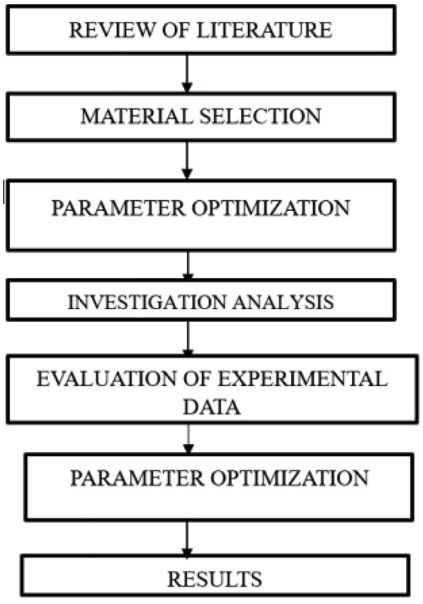


Fig 1. Methodology of Experiment.

2.1.3. Experimental details

On a PC numerically controlled vertical milling system, experiments were achieved on AA6061 and AA5052 aluminum alloys with thicknesses of 4 mm every. Desk 1 suggests the chemical composition of base substances. The plates had been completed to be 100 mm × 50 mm × 4 mm in length. Prepared samples for FSW process is shown in Fig. 2. A butt weld become created by using clamping the materials the use of furnishings, with AA5052 at the retrieving facet and AA6061 on the advancing facet, and the usage of the parameter values listed inside the field Behnken design matrix, as shown in Table 2, with an H13 device with a shoulder diameter of 18 mm and a probe duration of 3.7 mm. Fig. 3 shows the Welding of specimen.The take a look at specimens

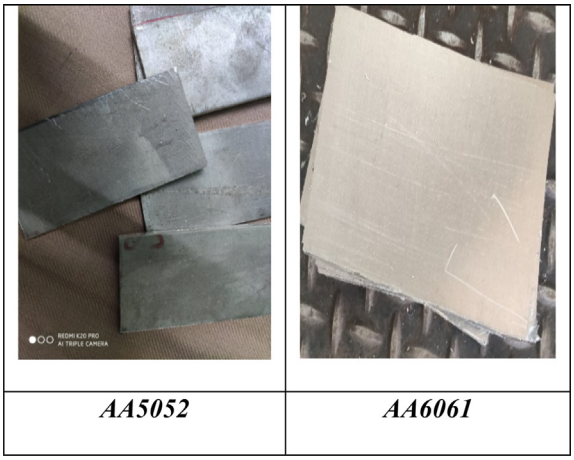


Fig 2. Prepared samples for FSW process.

Table 2
Tool Dimensions.

Shoulder diameter	18 mm
Probe diameter	5 mm
Probe length	3.7 mm



Fig 3. Welding of specimen.

Table 3
Orthogonal array for box Behnken design of 3 factors at 3 level design.

Run	Spindle Speed (rpm)	Welding Speed (mm/min)	Tilt Angle (degree)
1	1100	25	1
2	900	25	1
3	1000	25	2.5
4	1000	20	1
5	1000	25	2.5
6	900	25	4
7	1100	30	2.5
8	1100	20	2.5
9	900	20	2.5
10	900	30	2.5
11	1000	25	2.5
12	1100	25	4
13	1000	25	2.5
14	1000	30	4
15	1000	20	4
16	1000	25	2.5
17	1000	30	1

have been created according with ASTM standards.Table 3. shows the tool dimensions.

2.2. Design of Experiment

For modern-day response surface evaluation, the container Behnken layout is used for three factors at three tiers each [17–19]. This design for 3 elements consists of three blocks, each of which contains elements that are various through the three combos of high and occasional, and it's also vital to encompass center points wherein the factors are at their relevant values [20].

3. Testing and analysis

3.1. Tension test

Anxiety tests have been carried out in accordance with nonferrous material standards. The tension test turned into completed the use of a ordinary finding out device, and the welded samples were machined according with welding requirements. The results of the tension test are shown in Table 4.

3.2. Hardness Test

Hardness is a fabric's resistance to plastic deformation due to indentation. Hardness also can speak with a material's resistance to scratching or abrasion [20-22]. The Rockwell hardness tester modified into used to carry out the hardness test. To achieve indentation, the welded samples are subjected to a hundred KN load [23]. Hardness at different zones is shown in Fig. 4. The hardness of the bottom materials and the weld sector have been measured and recorded in Table 5. Parent 4 depicts the hardness values of the bottom metals and the weld region for numerous runs.

The Table 4 shows that the hardness at weld zone is higher than the base materials.

4. Optimization

ANOVA analysis is used to evaluate the Quadratic model developed for flexibility in response to strong power, yield strength, and maximum durability, as shown in Table 6. The R-Squared cut-off coefficient indicates the equilibrium, which means that there is little difference between the predicted and the actual data [24]. The signal-to-noise ratio is measured by "Adeq Precision." A rating greater than 4 is preferred. Because all of the Adeq accuracy values above are greater than 4, these models can be used to navigate the design space [25].

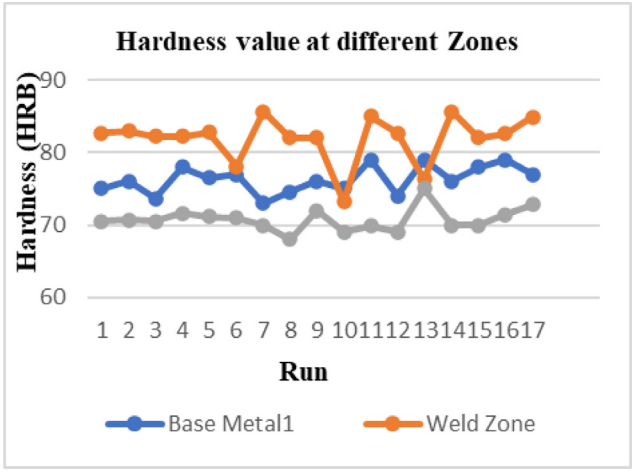


Fig 4. Hardness at different zones.

Table 4
Tension test results.

Run	Spindle Speed (rpm)	Welding Speed(mm/min)	Tilt Angle (degree)	Yield stress (Mpa)	Tensile strength (Mpa)	%Elongation
1	1100	25	1	115.72	130	7.19
2	900	25	1	88	128	5.85
3	1000	25	2.5	112	128.86	6.98
4	1000	20	1	105	130.64	6.73
5	1000	25	2.5	112	128.26	6.92
6	900	25	4	95	126.15	6.67
7	1100	30	2.5	112.17	129.11	7.21
8	1100	20	2.5	109.17	126	6.8
9	900	20	2.5	95	130.28	6.28
10	900	30	2.5	90	124.8	5.94
11	1000	25	2.5	105.88	129.43	6.8
12	1100	25	4	108	125	6.95
13	1000	25	2.5	112	129.24	6.73
14	1000	30	4	105.9	126.25	6.57
15	1000	20	4	109	127.78	6.78
16	1000	25	2.5	112	128.49	6.86
17	1000	30	1	107	129.76	6.94

4.1. Design summary

The response surface model for the box Behnken design is shown in the Table 6.

Response	Name	Analysis	Minimum	Maximum	Mean	Std. Dev.
Y1	Yield Strength (Mpa)	Polynomial	88	115.72	105.52	8.1157
Y2	Tensile Strength (Mpa)	Polynomial	124.8	130.64	128.12	1.793
Y3	% Elongation	Polynomial	5.85	7.21	6.7176	0.367

4.2. Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Spindle Speed	maximize	900	1100	1	1	3
Welding Speed	is in range	20	30	1	1	3
Tilt Angle	is in range	1	4	1	1	3
Yield Strength	maximize	88	115.72	1	1	3
Tensile Strength	maximize	124.8	130.64	1	1	3
% Elongation	maximize	5.85	7.21	1	1	3

4.3. Desirability Solutions

Number	Spindle speed	Welding speed	Tilt angle	Yield strength(MPa)	tensile Strength(MPa)	% elongation	Desirability	
1	1100	28.53	1.01	115.7222	131.0328	7.481417	0.989999	Selected

Number	Spindle speed	Welding speed	Tilt angle	HRB1	Weld zone	HRB2	Desirability	
1	1100	27	1.17	78.5066	83.47592	73.99999	0.985	Selected

4.4. Point prediction

Factor	Name	Level	Low Level	High Level	Std. Dev.	Coding
A	spindle speed	1100	900	1100	0	Actual
B	welding speed	28.53165	20	30	0	Actual
C	tilt angle	1.72973	1	4	0	Actual

Response	Prediction	SE Mean	95% CI low	95% CI high	SE Pred	95% PI low	95% PI high
Yield strength	115.0859	1.683991	111.1039	119.0679	2.776217	108.5212	121.6506
tensile Strength	129.9943	0.299573	129.2859	130.7027	0.493873	128.8265	131.1621
% elongation	7.333178	0.109413	7.074456	7.591899	0.180378	6.906651	7.759704

Table 5
Hardness test results.

Run	Spindle Speed (rpm)	Welding Speed (mm/min)	Tilt Angle (degree)	Hardness of Base metal Al 6061 (HRB)	Weld zone Hardness (HRB)	Hardness of Base metal Al 5052(HRB)
1	1100	25	1	75	82.72	70.51
2	900	25	1	76	83	70.66
3	1000	25	2.5	73.62	82.22	70.53
4	1000	20	1	78	82.18	71.59
5	1000	25	2.5	76.53	82.78	71.18
6	900	25	4	77	78.1	71
7	1100	30	2.5	73	85.67	70
8	1100	20	2.5	74.59	82	68
9	900	20	2.5	76	82	72
10	900	30	2.5	75	73.15	69
11	1000	25	2.5	79	85.02	69.88
12	1100	25	4	74	82.7	69
13	1000	25	2.5	79	76.28	75
14	1000	30	4	76	85.67	70
15	1000	20	4	78	82	70
16	1000	25	2.5	79	82.56	71.39
17	1000	30	1	77	84.86	72.85

Table 6
Design response surface model.

Factor	Name	Units	Type	Low Actual	High Actual
A	Spindle Speed	rpm	Numeric	900	1100
B	Welding Speed	mm/min	Numeric	20	30
C	Tilt Angle	degree	Numeric	1	4

Conformity Test: A conformance test was performed to confirm the accuracy of the obtained values. The results obtained from the conformity check are shown in the table below,

Spindle speed	1100
Welding speed	28
Tilt angle	10
Yield strength	114.567
Tensile strength	130.963
%Elongation	7.8
HRB1	75.776
Weld nugget	83.583
HRB2	72.8889

The regression equation for tensile strength, yield stress, hardness is obtained using the response surface methodology.

4.5. Final equation in terms of actual factors

Nomenclature:
A – Spindle speed = 1100 rpm.
B – Welding speed = 28 mm/min.
C – Tilt angle = 10

Yield strength = - 725.14344+1.48126 * A + 0.49350 * B + 33.36056 * C+ 4.00000E-003 * A * B - 0.024533 * A * C- 0.17000 * B * C- 7.11800E-004 * A2 - 0.082920 * B2 - 0.87911* C2.

Yield strength = 114.567 MPa

Tensile Strength = + 94.40600 + 0.16970 * A - 4.37183 * B + 5.25500* C+ 4.29500E-003 * A * B - 5.25000E-003 * A * C- 0.021667 * B * C- 1.31425E-004 * A2 + 2.30000E-004 * B2 - 0.11300 * C2.

Tensile strength = 130.963 MPa

HRB1 = + 39.73819+0.15260 * A - 2.91117 * B + 3.23361 * C+ 1.75500E-003 * A * B -3.33333E-003 * A * C+ 5.66667E-003 * B * C- 9.87500E-005 * A2 + 0.018800 * B2 - 5.55556E-003 * C2.

HRB1 = 75.776

Weld zone = + 81.09181+ 0.035038 * A - 0.75417 * B - 4.99361 * C+ 1.00000E-003 * A * B + 3.85000E-003 * A * C+ 0.066667 * B * C- 3.48750E-005 * A2 - 8.25000E-003 * B2 - 0.099444 * C2.

Weld zone = 83.853

HRB2 = + 35.99394 + 0.16811 * A - 2.71133 * B - 6.22056 * C+ 2.50000E-003 * A * B + 2.56667E-003 * A * C+ 0.13333 * B * C- 1.23850E-004 * A2- 4.94000E-003 * B2 + 5.11111E-003 * C2.

HRB2 = 72.8889

5. Results and discussions

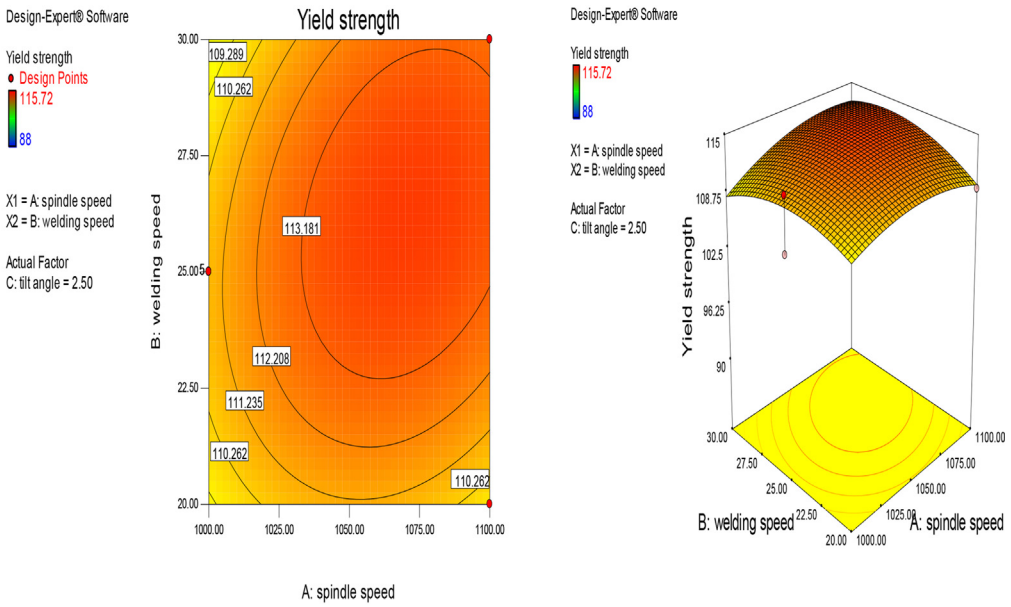
The conformity test results confirmed the results of the box Behnken design. The contour and 3D surface plots show the relationship between the process parameters.

5.1. Contour and 3D surface plot

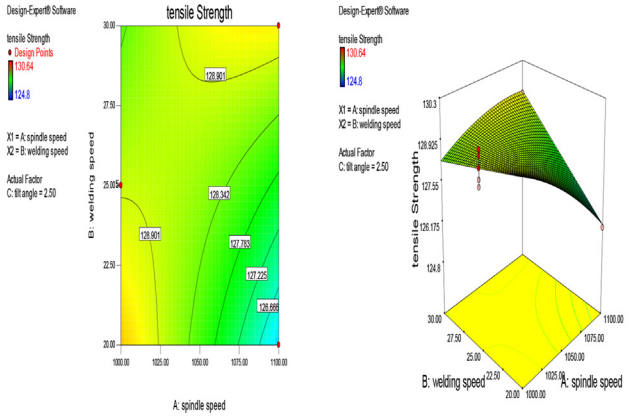
The 3D and contour surface plots were created by holding the spindle and welding speeds constant while uniformly varying the tilt angle. To achieve optimal results, the maximum tensile strength, yield stress, and hardness values are compared. They are depicted in the images below. Fig. 5 shows the Contour and 3D surface plots for tension test and Fig.6 shows the Contour and 3D surface plots for hardness test.

Effect of rotational speed and welding speed on tensile strength, yield strength and hardness at the weld zone. According to test results, rotation speed, welding speed, and angle of inclination all have a significant impact on the mechanical properties of the welding joint. The conflicting temperatures required to make plastic material are produced at rotational speed, which also contributes to the proper mixing of different alloys. The properties of low-

Yield strength



Tensile strength



Elongation at break

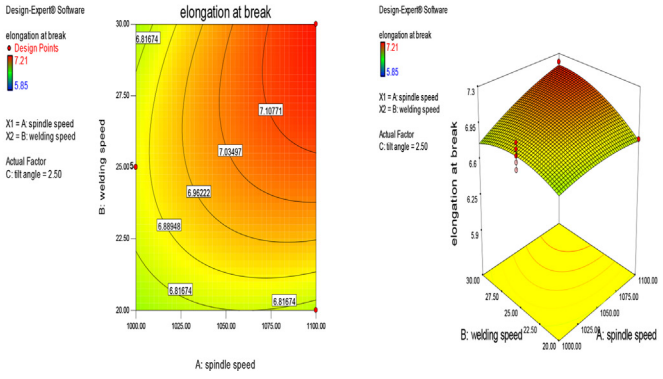
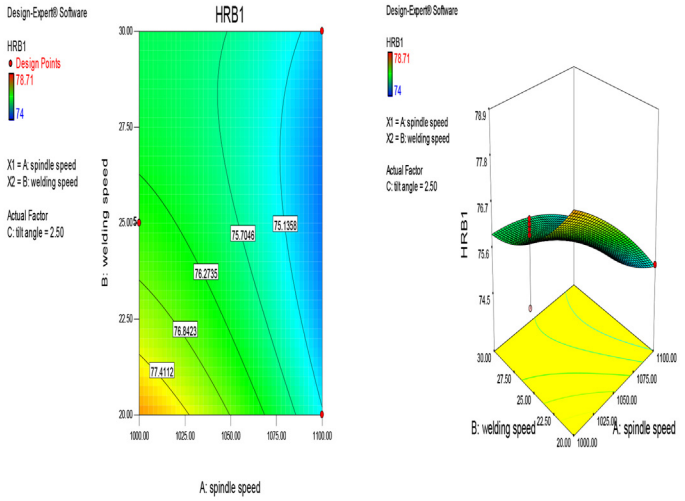
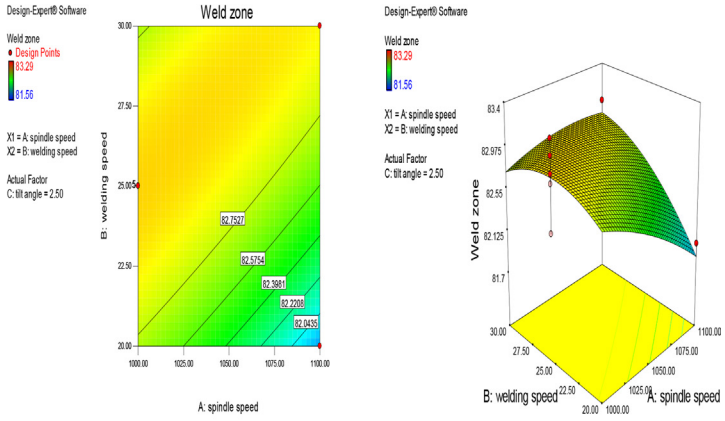


Fig 5. Contour and 3D surface plots for tension test.

Hardness at base metal 1



Hardness at weld nugget



Hardness at base metal 2

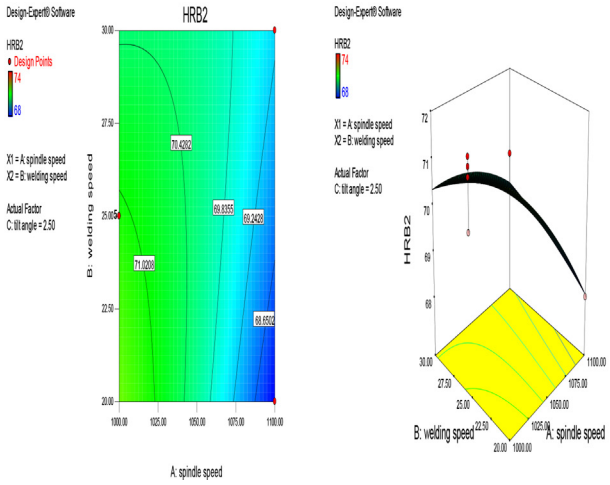


Fig 6. Contour and 3D surface plots for hardness test.

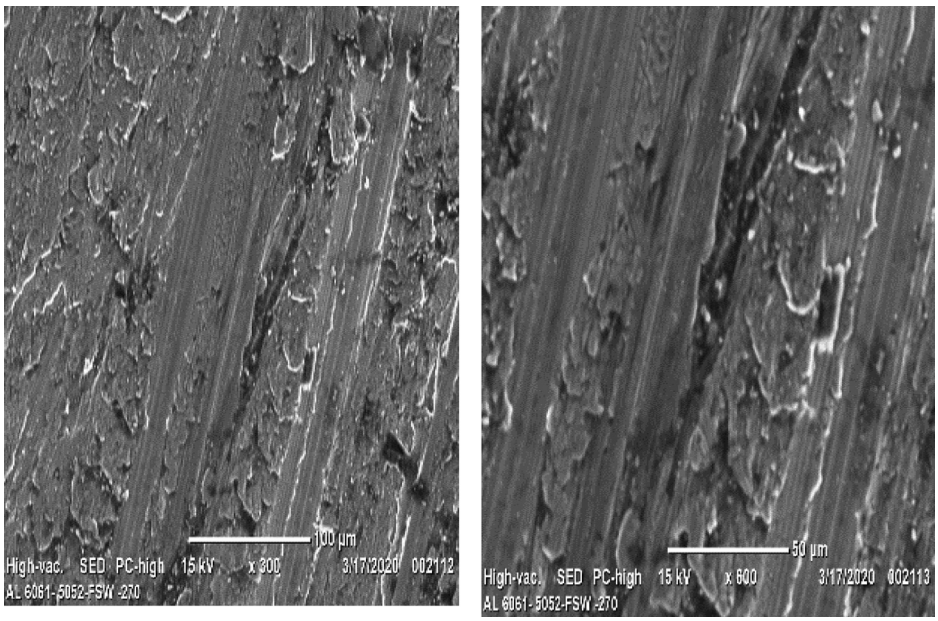


Fig 7. SEM Images of Welded Portion.

speed weld machines are higher than those of high-speed weld machines. According to the results of experiments and book reviews, mechanical properties increase with rotational speed and welding speed, but only up to a certain point before decreasing.

6. Effect of tilt angle on tensile strength, yield strength and hardness

The upper level of the weld joint is affected by the angle of inclination of the tool. As the tilt angle of the tool increases, there is less flow of semisolid material and less material filling due to less heat dissipation, so heat defects such as faults and worm holes increase. These defects reduce the strength of the weld joint.

6.1. Desirability approach

The Desirability method is used to solve many response problems due to its simplicity, flexibility, and ease of access to the software. This method converts multiple response values into a seamless performance measure known as the total desirable function, with a range of 0 to 1. The best results predicted from the above strategies are a strong storage capacity of 130 MPa, a production capacity of 114 MPa, and a hardness of 83 welding. The software development component of the design specialist produces a desirable total value of 0.975 Fig. 7 shows the SEM Images of Welded Portion.

6.2. Microstructure

The unreadable tool was used to heat up the current study. As a result, no significant mixing of the two alloys was detected. According to microstructural studies, there was no solid mixing of both building materials in nugget. The intensity of the nugget changed abruptly throughout the visible connector.

Therefore, the combination of alloying elements and nugget acquisition of the same shape may contribute to the fine mechanical properties of friction stir welded. Images AA5052-AA6061. The solid structures of the FSW AA5052-AA6061 models were higher than those of the very soft friction-stir-welded systems (i.e., FSW AA6061). Fig. 7 shows an image electron microscope image of a weld nugget.

7. Conclusion

Complete list of quality process parameters for different AA 6061 welding joints and AA 5052 achieved. Enhancing multiple targets with RSM is a useful way to develop friction welding parameters to achieve strong storage strength, productivity, and hardness in a welding combustion of different combinations stimulates a welded component at a 95 percent confidence level.

The following conclusion has been reached as a result of the current investigation work:

- The friction stir welding process can effectively weld aluminum alloys grades AA 6061 and AA 5052.
- Rotational speed and welding speed both contribute significantly to the production of the required conflicting heat and have a significant impact on mechanical properties.
- The mechanical properties increase as the parameter levels change from the bottom to the top, but only to a certain point before they begin to decrease.
- The maximum level of welding joints is determined by the angle of inclination of the tool. As the tilt angle of the tool increases, there is less flow of semisolid material and less material filling due to less heat dissipation, so heat defects such as faults and worm holes increase.
- The ideal conditions for sound weld generating equipment were determined to be a spinning speed of 1100 rpm, a welding speed of 25–30 mm / min, and a tilt angle of 1–1.50.
- Professional design software results have been found to have a high value and satisfy a high response rate.

CRediT authorship contribution statement

A. Ruskin Bruce: Writing – original draft, Supervision, Validation. **P. Prem Kumar:** Writing – original draft, Supervision. **K. Arul:** Writing – original draft, Supervision, Validation. **P. Manoj Kumar:** Writing – original draft, Supervision, Validation. **S. Lakshamana**

Kumar: Methodology, Writing – review & editing. **S. Aravindh:** Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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