EXPERIMENTAL INVESTIGATIONS AND MULTIPLE RESPONSE OPTIMIZATION OF FRICTION STIR WELDING PARAMETERS AA7075-T6 ALLOYS USING PCA AND GRA

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Abstract

Friction Stir Welding is a variation of friction welding method. Accomplishing the optimal processing parameters for the best probable design is still a challenging task. This paper presents a novel methodology for the Experimental Investigation and Multiple Response optimization of welding parameters on dissimilar friction stir welded joints between AA7075-T6 aluminum alloys. The optimization was done using GRA & PCA.In this study, welding parameters namely rotational speed, welding speed, shoulder diameter, tool tilt angle, tool pin profile and tool material were optimized with the considerations of multi responses such as Ultimate Tensile Strength (UTS), Hardness (VHN) and Impact Load. L27 Orthogonal array was taken to conduct the experiments with the range 700 – 1100 revolutions per minute (rpm) for rotational speed and with welding speed from 20, 40 & 60 millimetre/minute (mm/min). The results obtained from GRA & PCA shows good convergence with the trial and the optimum process parameters combinations, where the maximum Ultimate Tensile Strength and the Hardness are obtained. The ranking of GRC and PCA were also displayed which shows same ranking was followed in both optimization techniques.

Keywords: Aluminum Alloys: Friction Stir Welding (FSW); Grey relational analysis method (GRA); Principal Component Analysis (PCA); DEA rank based method; Ultimate Tensile Strength (UTS); Hardness (VHN).
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I. INTRODUCTION

Friction Stir Welding (FSW) was introduced in 1992 as a safe, state-of-the-art welding process by The Welding Institute (TWI) in the United Kingdom (Mishra et al. 2013). The spinning and passing cylindrical tool with a profile pin in FSW "moves" the connected surfaces using frictional and adiabatic heat. Figure 1. depicts the friction stir welding process schemes. The rotary tool performs two main functions: (a) heating the work piece and (b) moving the plasticized result to the junction. The heating process is accomplished through friction between the tool and the work piece. This localized heating softens the material around the moving pin, and the combination of tool rotation and motion results in the front-to-back plasticization of the pin. It is shown schematically in the below image.The process finds its major application for joining hard-to-weldmetals, especially the precipitation hard enable aluminium alloy [1].

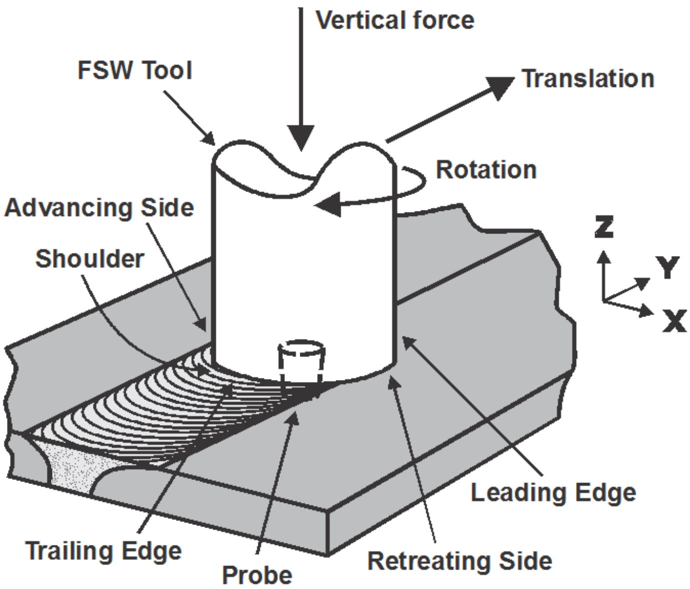

Fig 1. Friction Stir Welding Schematic Representation

Tool rotary speed and tool traverse speed govern thepeaktemperaturegeneratedduringFSWandthet imerequiredtoweldthematerial.Thewayinwhichte mperature affects material properties varies significantly for different aluminium alloys [2].The tool geometry plays a vital role in determiningtheamountofheatgenerationduringFS W. The appropriate temperature for a defect free friction stir weld of Al 7075 T651 could be in therange of 375 to 420^{0}C.The joints fabricated with 20mm shoulder diameter yield maximum jointefficiency. Investigations on the effect of pin profile on the quality of friction stir welded Al7075-T6 alloys revealed that the shape of pin profile plays a significant role in producing defect free joint [3]. The tool material is one of the important parameter which affects the weld joint. The mechanical properties of the joint may vary due to the changes in tool material. The tool material hardness must be sufficient to produce quality weld joint [4]. Taguchi Grey Relation Analysis and Principal Component Analysis are one of the robust methods to optimize the process parameters of friction stir welding. Grey relational Analysis (GRA) was deployed to convert multi objective case into single objectiveone by calculating Grey Relational Grade (GRG). The weights of the influencing parameters will becalculatedusingPrincipalComponentAnalysis(PC A).Theoptimumprocessparameterswereobtained from Response surface plots drawn for GRG [5].

II. SELECTION OF MATERIAL AND PROCESS PARAMETERS

A) MATERIAL SELECTION

Aluminium alloys AA7075 – T6 selected to fabricate dissimilar joints using the FSW process due to its high strength and toughened alloys. The combination of its high strength-to-weight ratio and natural ageing characteristics makes it more feasible for a variety of structural applications in aircrafts. When it comes to military, aerospace, and marine applications, FSW is increasingly being employed for AA7075 aluminum alloy in non-uniform loads and corrosive conditions [6].

Table 1. AA7075 Composition

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Percentage	0.04	0.17	1.4	0.04	2.4	0.20 – 0.21	5.7	0.04 – 0.05	Bal

Table 2. Mechanical Properties of AA7075

Yield strength	412 MPa
Ultimate tensile strength	488 MPa
% elongation at break	13.3
Fracture toughness	22.8 Mpa-m1/2

Brinell hardness	104
Young's modulus	717x102Mpa
Poisson's ratio	0.3
Strength to weight ratio	196 KN-m/kg

B) PROCESS PARAMETERS

Rotational Speed

The rotational speed is one of the significant parameters which influences the strength of joint. There is a strong link between welding characteristics and rotational speeds. Grain coarsening, dissolution, and the deposition of hardening precipitates in grain boundaries were seen when the rotating speed was increased, as were higher pick temperatures. The average grain size of nugget increases with increasing rotary speed [7]. In the present study the rotational speeds of 700 rpm, 900 rpm and 1100 rpm have been considered to conduct friction stir welding of Al 7075-T6 joints.

Tool Traverse Speed or Feed

Tool traverse speed or welding speed or feed significantly affects the mechanical properties and the microstructure of the joining. The average grain size of the weld nugget reduces with increased welding speed. In addition, weld nugget was negatively influenced in terms of its mechanical properties with this high welding speed [8]. The three different weld speeds considered in the present research work are 20 mm/min, 40 mm/min and 60 mm/min.

Tool Tilt Angle

The tool's tilt angle has shown its impact on material flow and heat generation. The material flow is greatly enhanced in the rear side of the FSW tool with the title angle, which helps in reducing reduce flaws in production, because of the higher temperature, softer material, and more force of friction in the trailing side of tool [9]. In the present research work the tilt angle is varied between 0^0 and 2^0 with an equal increment of 1^0.

Tool Shoulder Diameter

The tool's shoulder generates most of the heat. Because less frictional heat is generated when shoulder diameter shrinks, joint strength correspondingly declines as the contract surface area between the shoulder and the workpiece shrinks as well. The greatest temperature was discovered to have occurred at a larger shoulder diameter from the thermal history [10]. The present experimental work is conducted with three different shoulder diameters of 16 mm, 18 mm, and 20 mm.

Tool Pin Profile

Weld strength is affected by several factors including the tool geometry. This comprises the shoulder diameter of the tool and the tool pin shape. A pulsing stirring action is produced by the flat faces of triangular and square pin shapes in flowing material. If you have a cylindrical pin profile, there will be no pulsating activity. Pin profiles with flat faces were found to be effective in reducing the occurrence of two typical FSW defects, namely kissing bond, and tunnel effect [11]. The present experiments are carried out by triangular, square and hexagonal pin profiles.

Tool Material

FS welded metals require knowledge of tool material selection in order to achieve sound joints. The final joint should not be contaminated by the substance used to make the tool. Due to the lack of wear resistance provided by softer tool materials, this is most commonly a result of poor tool design. Weak materials may usually be joined with relatively harder tools, while hard ones necessitate the use of extremely hard ones in order to make a successful joint [12]. Three different tool materials OHNS [31], EN31 [37] and H13 [31] materials were taken to produce the weld joins in the present research work.

Table1.Input Process Parameters

S. No	Operating Conditions	Identified Values
1	Rotational Speed (rpm)	700, 900 & 1100
2	Welding Speed (mm/min)	20, 40 & 60
3	Tool Tilt Angle in degrees	0, 1 & 2
4	Tool Shoulder Diameter (mm)	16, 18 & 20
5	Tool Pin Profile	Triangular, Square & Hexagon
6	Tool Material	OHNS, EN31 & H13

III. EXPERIMENTAL WORK

The experiments were designed using Minitab 17 software package. L27 orthogonal array of experiments were selected with six process parameters of three levels. The tools were designed and manufactured using conventional lathe machine. Aluminum 7075-T6 plates of 4 mm thickness were cut into 150 mmX75mmX 4 mm[] by a power hacksaw and milling machine. Before welding, the weld surface cleaned to remove dirt and any oil traces present on the plates. The edges are also prepared to be parallel to one another. This is to guarantee that the plates do not have an unequal spacing between them, which might lead to poor welding. Second, the surfaces of both plates were prepared so that they were at the same level.Then the welding was performed using vertical milling machine.

Table 2. Design of Experiments

Exp.No	A	B	C	D	E	F
1	1	1	1	1	1	1
2	1	1	1	1	2	2
3	1	1	1	1	3	3
4	1	2	2	2	1	1
5	1	2	2	2	2	2
6	1	2	2	2	3	3
7	1	3	3	3	1	1
8	1	3	3	3	2	2
9	1	3	3	3	3	3
10	2	1	2	3	1	2
11	2	1	2	3	2	3
12	2	1	2	3	3	1
13	2	2	3	1	1	2
14	2	2	3	1	2	3

15	2	2	3	1	3	1
16	2	3	1	2	1	2
17	2	3	1	2	2	3
18	2	3	1	2	3	1
19	3	1	3	2	1	3
20	3	1	3	2	2	1
21	3	1	3	2	3	2
22	3	2	1	3	1	3
23	3	2	1	3	2	1
24	3	2	1	3	3	2
25	3	3	2	1	1	3
26	3	3	2	1	2	1
27	3	3	2	1	3	2

IV. RESULTS AND DISCUSSION

Table 3. Experimental Results of UTS, VHN and Impact energy

S. No	TRS (rpm)	WS (mm/min)	TLT (degree)	SD (mm)	PP	TM	UTS (Mpa)	VHN	Impact Energy (J)
1	700	20	0	16	Triangle	OHNS	172.06	90.73	4
2	700	20	0	16	Square	EN31	137.04	93.9	4
3	700	20	0	16	Hexagon	H13	193.95	87.7	8
4	700	40	1	18	Triangle	OHNS	257.49	95.73	8
5	700	40	1	18	Square	EN31	277.44	98.33	6
6	700	40	1	18	Hexagon	H13	378.55	99.53	8
7	700	60	2	20	Triangle	OHNS	267.6	105.67	4
8	700	60	2	20	Square	EN31	340.62	99.33	3
9	700	60	2	20	Hexagon	H13	243.48	85.93	7
10	900	20	1	20	Triangle	EN31	327.67	104.67	6
11	900	20	1	20	Square	H13	297.77	99.6	4
12	900	20	1	20	Hexagon	OHNS	268	86.63	8
13	900	40	2	16	Triangle	EN31	259.14	103.67	4
14	900	40	2	16	Square	H13	368.91	93	6
15	900	40	2	16	Hexagon	OHNS	267.61	92.83	4
16	900	60	0	18	Triangle	EN31	244.24	96.47	6
17	900	60	0	18	Square	H13	264.79	104.67	4
18	900	60	0	18	Hexagon	OHNS	113.85	93.9	8
19	1100	20	2	18	Triangle	H13	317.38	97.2	8
20	1100	20	2	18	Square	OHNS	266.27	86.77	8
21	1100	20	2	18	Hexagon	EN31	280.2	84.8	6
22	1100	40	0	20	Triangle	H13	133.49	93.9	4
23	1100	40	0	20	Square	OHNS	213.03	96.2	6
24	1100	40	0	20	Hexagon	EN31	155.17	84.5	10
25	1100	60	1	16	Triangle	H13	382.24	106.67	5

26	1100	60	1	16	Square	OHNS	286.45	100.5	6
27	1100	60	1	16	Hexagon	EN31	209.87	102.67	7

The table 3 depicts the experimental results of UTS, VHN and Impact Energy of the welded joints. Tension test was conducted to find the ultimate tensile strength of the weld joints at the stir zone and the results were tabulated in the table The experimental findings have shown that the highest value of UTS of 382.243 MPa was obtained for the 25th trial Whereas the least ultimate strength of 155.176 MPa is obtained at 24th trail mm shoulder diameter hexagonal pin profile tool made up of EN 31 tool material kept at 0°tool tilt angle.The hardness of the welded joints at the stir zone was determined using Vicker's hardness testing method. The results indicated that the maximum value of hardness of 106.67 HV was observed at the 25th trial and minimum hardness value was observed at 24th trial. From the results of impact test, the maximum impact energy absorbed by the joint was obtained at the 24thtrialwhereas the least impact energy of the joint was observed at the 8th trial.

V. MICROSTRUCTURAL CHARACTERIZATION

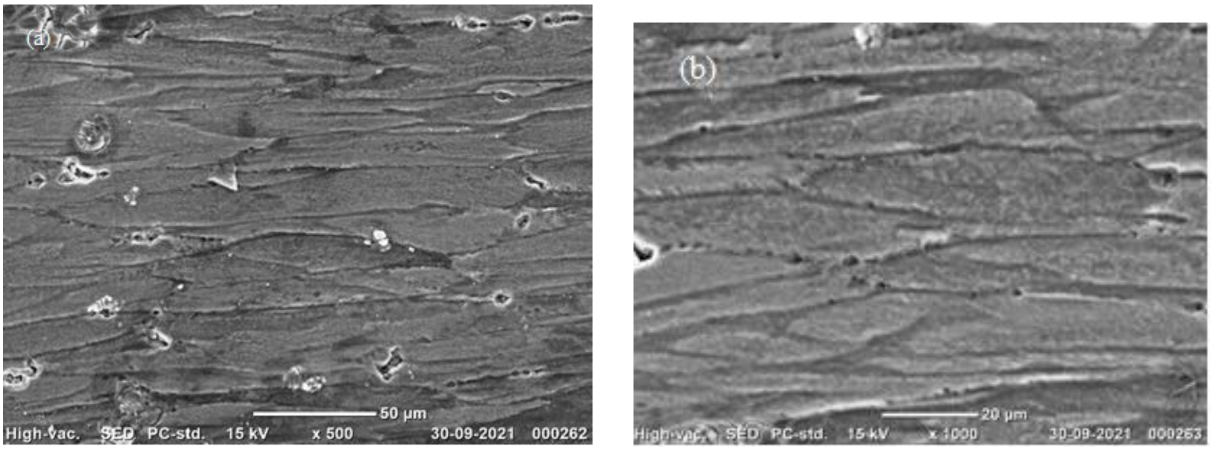

Fig. 1(a) & (b) Microstructure of Al7075-T6 alloy

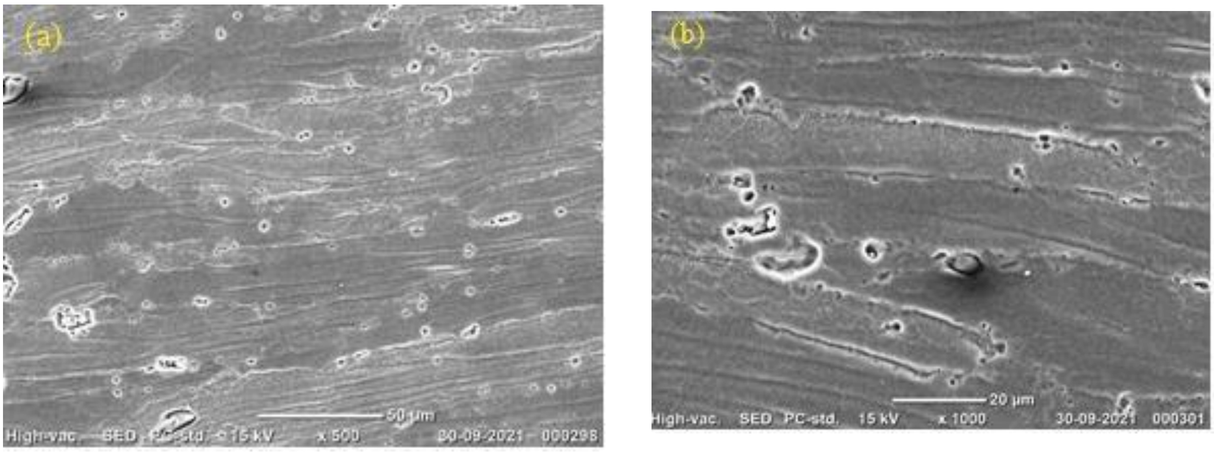

Fig. 2 (a) & (b) Microstructure of Al 7075-T6 alloy at HAZ of highest UTS and hardness specimen

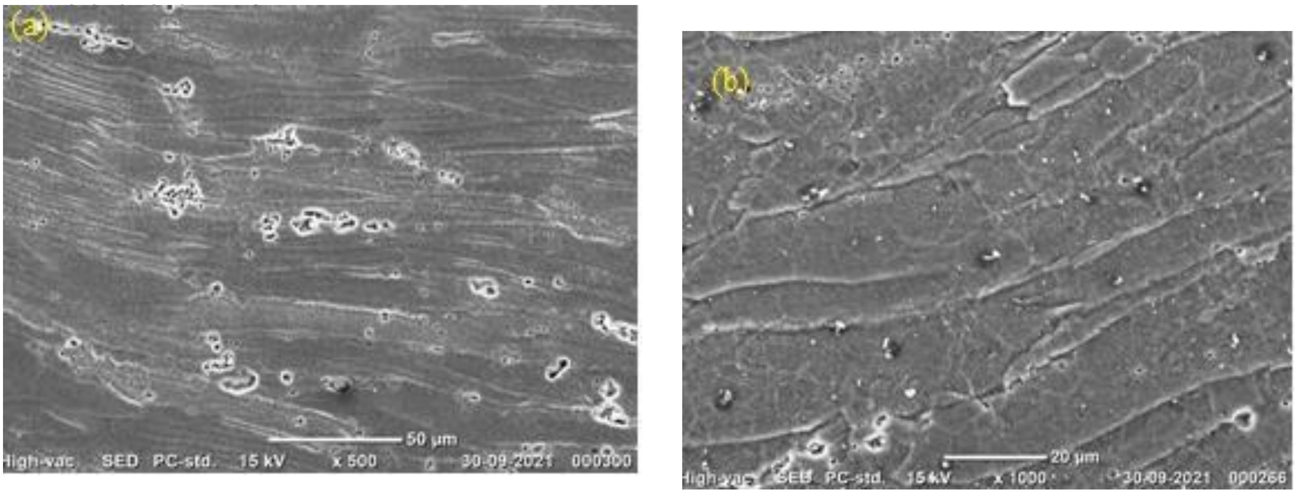

Fig. 3 (a) & (b) Microstructures of Al 7075-T6 alloy at TMAZ of highest UTS and hardness

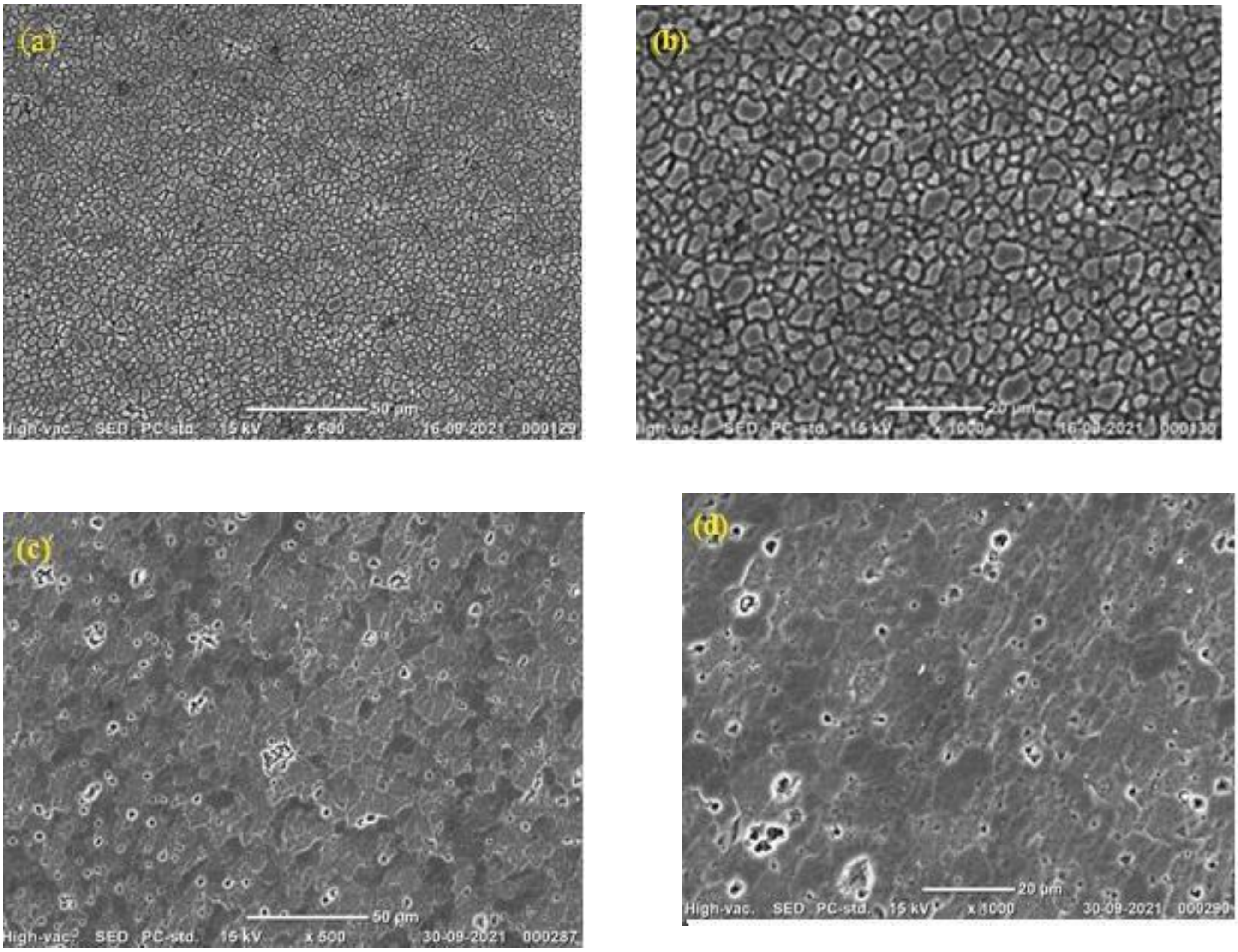

Fig. 4 (a), (b), (c) & (d) Microstructures of Al 7075-T6 alloy at Stir Zone

VI. OPTIMIZATION OF PROCESS PARAMETERS USING GRA& PCA

Multi-objective optimization problems are reduced to single-objective problems via grey relational analysis. The study's goal was to find the best combination of welding parameters for maximizing UTS, hardness and impact energy of the welded joint at the same time.

Table 4. Normalized values of UTS, VHN and Impact Energy

S. No	Exp. No.	UTS	VHN	Impact energy	NormalUTS	NormalVHN	NormalImpact Energy
1	1	172.065	90.73	4	-207.28	-316.631	-10.666
2	2	137.041	93.9	4	-164.775	-327.754	-10.666
3	3	193.952	87.7	8	-233.842	-306	-22.787
4	4	257.496	95.73	8	-310.958	-334.175	-22.787
5	5	277.446	98.33	6	-174.343	-343.298	-16.727
6	6	378.555	96.53	6	-238.336	-347.508	-22.7
7	7	267.602	105.67	4	-168.112	-369.052	-10.666
8	8	187.628	109.33	2	-214.32	-346.807	-7.636
9	9	243.487	85.93	10	-152.85	-299.789	-19.757
10	10	327.679	104.67	6	-206.136	-365.543	-16.727
11	11	297.772	99.6	4	-187.207	-347.754	-10.666
12	12	268.008	86.63	8	-168.369	-302.245	-22.787
13	13	259.145	103.67	4	-162.76	-362.035	-10.666
14	14	368.917	93	6	-232.236	-324.596	-16.727
15	15	267.619	92.83	4	-168.123	-324	-10.666
16	16	244.241	96.47	6	-153.327	-336.771	-16.727
17	17	264.797	104.67	4	-166.337	-365.5438	-10.666
18	18	113.857	93.9	8	-70.805	-327.754	-22.7878
19	19	317.387	97.2	8	-199.622	-339.333	-22.787
20	20	266.277	86.77	8	-167.274	-302.736	-22.787
21	21	280.208	84.8	6	-176.091	-295.824	-16.727
22	22	133.493	93.9	4	-83.233	-327.754	-10.666
23	23	213.036	96.2	6	-133.577	-335.824	-16.727
24	24	55.176	105	10	-96.953	-294.771	-28.848
25	25	382.243	106.67	8	-240.67	-372.5614	-13.696
26	26	286.453	100.5	6	-180.043	-350.912	-16.727
27	27	209.879	102.67	10	-131.579	-358.526	-19.757

In grey relational analysis, the initial step is to normalize the experimental databased on the type of performance response (between 0 and 1). If the original sequence's target value is infinite, such as UTS or VHN, the "larger-is-better" characteristic applies. The table 5.10 shows the normalized values of output parameters i.e., ultimate tensile strength, hardness, and impact energy of welded joints.

Table 5. Deviation Square Values of Normalized values of UTS, VHN and Impact Energy

S. No	Exp. No	Dev. Sq. UTS	Dev. Sq. VHN	Dev. Sq. ImpactEnergy
1	1	208.280	317.631	11.666
2	2	165.775	328.754	11.666
3	3	234.842	307	23.787
4	4	311.958	335.175	23.787
5	5	175.343	344.298	17.727
6	6	239.336	348.508	23.787
7	7	169.112	370.052	11.666
8	8	215.326	347.807	8.636
9	9	153.85	300.789	20.757
10	10	207.136	366.543	17.727
11	11	188.207	348.754	11.666
12	12	169.369	303.245	23.787
13	13	163.760	363.035	11.666
14	14	233.236	325.596	17.727
15	15	169.123	325	11.666
16	16	154.327	337.771	17.727
17	17	167.337	366.543	11.666
18	18	71.805	328.754	23.787
19	19	200.622	340.333	23.787
20	20	168.274	303.736	23.787
21	21	177.091	296.824	17.727
22	22	84.233	328.754	11.666
23	23	134.577	336.824	17.727
24	24	97.953	295.771	29.848
25	25	241.67	373.561	14.696
26	26	181.043	351.912	17.727
27	27	132.579	359.526	20.757

To determine the relationship between the ideal and the actual experimental findings, the divisional square values of output responses have been found and from the these values the grey relational coefficients are determined.

Table 6. Grey Relational Coefficients of UTS, VHN and Impact Energy

S.No	Exp.No	GRC (UTS)	GRC (VHN)	GRC (Impact Energy)
1	1	0.002	0.0015	0.041
2	2	0.003	0.0015	0.041
3	3	0.002	0.0016	0.020
4	4	0.001	0.0014	0.020
5	5	0.002	0.0014	0.027
6	6	0.002	0.0014	0.020
7	7	0.002	0.0013	0.041
8	8	0.002	0.0014	0.054
9	9	0.003	0.0016	0.023
10	10	0.002	0.0013	0.027
11	11	0.002	0.0014	0.041
12	12	0.002	0.0016	0.020
13	13	0.003	0.0013	0.041
14	14	0.002	0.0015	0.027
15	15	0.002	0.0015	0.041
16	16	0.003	0.0014	0.027
17	17	0.002	0.0013	0.041
18	18	0.006	0.0015	0.020
19	19	0.002	0.0014	0.020
20	20	0.003	0.0016	0.020
21	21	0.002	0.0016	0.027
22	22	0.006	0.0015	0.001
23	23	0.003	0.0014	0.027
24	24	0.005	0.0016	0.016
25	25	0.002	0.0013	0.032
26	26	0.002	0.0014	0.027
27	27	0.0037	0.0013	0.023

Table 6. shows the gray relational coefficient values for the output process parameters. After computing the grey relational coefficients, the distinguishing coefficient is set to 0. The Grey relationship grade is discovered in the third stage. The higher the relational grade, the closer the experimental value is to the ideal normalized value and to the optimal when the relevant parameter combination is used in the normalized value.

Table 7. Grey Relational Grades, Ranks and Principal Component Analysis Ranks

S.No	Exp.No.	GRG	GRG Rank	GRG-PCA	PCA Rank
1	1	0.0148	9	0.0156	9

2	2	0.0150	3	0.0158	3
3	3	0.0080	24	0.0084	24
4	4	0.0078	26	0.0082	26
5	5	0.0104	14	0.0109	14
6	6	0.0079	25	0.0083	25
7	7	0.0149	7	0.0157	7
8	8	0.01929	1	0.0203	1
9	9	0.0093	20	0.0097	20
10	10	0.0102	16	0.0108	16
11	11	0.0149	8	0.0156	8
12	12	0.0083	22	0.0086	22
13	13	0.0150	5	0.0157	5
14	14	0.0102	17	0.0108	17
15	15	0.0150	4	0.0158	4
16	16	0.0106	12	0.0110	12
17	17	0.0149	6	0.0157	6
18	18	0.0095	18	0.0099	18
19	19	0.0080	23	0.0085	23
20	20	0.0083	21	0.0087	21
21	21	0.0105	13	0.0110	13
22	22	0.0160	2	0.0166	2
23	23	0.0107	11	0.0112	11
24	24	0.0076	27	0.0078	27
25	25	0.0119	10	0.0126	10
26	26	0.0104	15	0.0109	15
27	27	0.0094	19	0.0098	19

The grey relational ordering is discovered in the fourth stage. The order 1 is the highest grey relational grade. Table 5.10 lays out the grey-to-blue relationship hierarchy. For maximum output responses, the sixth experiment's control parameter setting had the highest grey relational grade, according and this implied that experiment 6 was the ideal setting for welding factors for maximum ultimate tensile strength, hardness, and impact energy. The combination of rotational speed of 700 rpm, weld speed of 40 mm/min, tool tilt angle of 1^0, tool pin profile of Hexagon, tool shoulder diameter of 18 mm and with hexagonal pin profile made up of H13tool material is the optimal combination for maximizing all the output responses.

VII. CONCLUSIONS

In the present research work an attempt was made to study the effect ofprocess parametersonthemechanicalpropertiesofAl 7075-T6alloy joints produced by using friction stir welding and to optimize theseprocessparameterstomaximizethemechanicalproperties.Thesubsequentconclusionswereillustrated from the investigation.

- The Al 7075-T6alloy plates of 4mm thickness were successfully welded using modified vertical milling machine and different combination of process parameters including rotational speed, weld speed, tilt angle, shoulder diameter, tool pin profileandtoolmaterialwithoutanymajorweldingdefects.

- Theexperimentalresultshaveshownthatth emaximumultimatetensilestrengthof 382.24 MPa and Vickers hardness of 106.67 HV were obtained at 1100 rpm rotationalspeed, 60 mm/min weld speed, tool title angle at 1^0, shoulder diameter of 16 mm, triangular pin profile tool made upof with H13 tool steel.
- The minimum ultimate tensilestrength of 155.17 MPa and hardness of 84.5 VHN were observed at24th trialconcerningallprocessparameters.
- Themaximumimpactenergyof10Joulewaso btainedatrotationalspeedof1100rpmweld speed 40 mm/min, tool title angle at 0^0, shoulder diameter of 20 mm, hexagonalpin profile tool made up of EN31 material. The minimum impact energy of 3 Joule was found forthe 8th trialconcerningallprocessparameters.
- The Gray Relational Rank and Principal Component Analysis Rank were determinedfortheexperimentalresultstode terminetheoptimized combination of processparametersto obtain the better mechanical properties atthesametime.Thefirst rankwasgiventothe eighth experiment trial with combination 700 rpm rotational speed, 60 mm/min weld speed,2^0tooltiltangle, 20 mmshoulderdiameter, square pinprofiledtoolmadeupofwith EN31 material.

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