AN EXPERIMENTAL STUDY ON FRICTION STIR WELDING OF ALUMINUM-MAGNESIUM ALLOYS FOR IMPROVED MECHANICAL PROPERTIES OF TAILOR WELDED BLANKS

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ABSTRACT

Tailor welded blanks (TWB) are used in automotive and aerospace industries as they offer weight saving followed by cost saving and improved fuel economy. Being light in weight and having low cost, Aluminum alloys have piqued the interest of scientists. Friction Stir Welding (FSW) is a well-known accepted technique used since 1991 worldwide for Aluminum and its alloys. Due to friction stir welding, mechanical changes occur due to stirring action at the joint. Also the inter-metallic compounds, kissing bond formation, onion ring formation etc. are defects encountered in the nugget zone of welding. Hence, a novel technique is suggested to carry out the friction stir welding using a blend of techniques viz. double sided friction stir welding and multi objective optimization of process parameters. For experimentation, AA 5182 and AA 5754-Aluminum Magnesium alloys of 5000 series are used with sheet size of 1.5 mm thickness. Experimentation was carried out on a vertical machining center, with circular, square, and triangular tool pin profiles with a tool rotational speed range between 1500 -1800 rpm and a welding speed range of 40 mm/min.-60 mm/min. For the analysis purpose, L9 orthogonal array was used and Grey Relational Analysis(GRA) was employed and ASTM standards were used for tensile testing. Base sample materials of AA 5182 and AA5754 are having ultimate tensile strengths of 289.58 N/mm2 and 220.75N/mm2respectively. The designed welded blank of the two materials recorded maximum ultimate tensile strength of 268.11N/mm2which was remarkable for FSW. Welded joint efficiency was found to be 92.73% and percentage elongation of TWB was found to be 44% as compared to the base metals.

KEYWORDS

Grey relational analysis, Double sided friction stir welding, Tensile Strength, Percentage Elongation.

PAPER INDEX

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1. INTRODUCTION

To achieve cost reduction and improved fuel efficiency, dissimilar materials of variable strengths can be employed at various locations in the automotive body. Nowadays, aluminum and its alloys are widely used in automobile body components. Due to the scarcity of aluminum in the market, it is frequently mixed with Magnesium to offer adequate strength. As custom welded blanks, aluminum-magnesium alloys with high specific strength, corrosion resistance, and a low weight-to-density ratio are employed. Due to metallurgical constraints, fusion welding of these Aluminum-Magnesium alloys is not practicable. Tailor Welded Blanks of dissimilar materials are frequently utilized to decrease cost, weight, and improve mileage in automobiles. Friction Stir Welding is a solid state joining technology that is more effective than fusion welding at joining dissimilar materials. A properly welded joint characteristics are dependent on a number of process parameters like, tool rotational speed, pin profile, shoulder shape, and welding speed [1]. Aluminum alloys, which are lighter in weight, more durable, and have better corrosion resistance, have largely supplanted steel in recent years.

Friction Stir Welding was invented by The Welding Institute in 1991.In the case of aluminum alloys, friction stir welding (FSW) has been found to be a better welding technique. However, as hardness increases in the weld zone, oxide formation is noticed in the Nugget Zone (NZ), residual stresses, kissing bond development, and production of intermetallic compounds are observed in the weld region. To establish a good welded joint is a difficulty that practically all researchers confront. FSW is being studied in order to improve welded joints. Many researchers have suggested multi-objective optimization of process parameters and double-sided friction stir welding approaches to solve faults in the welded connection.

Yuvaraj et al. [1] performed friction stir welding of dissimilar materials of AA7075-T651 and AA 6061 alloys using different FSW parameters and found that square pin profile gave higher strength, whereas Haribalaji et al. [2] used friction stir welding on input parameters and machine nature. Researchers Klos et al.[3] and Kaushik et al. [4] investigated the effects of tool pin profiles, feed rate, tool tilt angle, and welding speed, as well as a review of the mechanical and metallurgical characteristics of friction stir welded connections. They analyzed that there were micro structural changes which were found in AA 6063 when combined with SiC particles. The usage of interlayer material in dissimilar Aluminum and Magnesium alloys was studied by Kumar et al. [5]. But Cabibbo et al. [6] discussed two unique techniques: double-sided friction stir welding and RT type pin arrangement. The utility of aluminum magnesium alloys was explored in depth, as well as the metallurgical changes that occur and the utility of these Al-Mg alloys in diverse applications such as marine, automotive, and aerospace [7,8] was studied. Different materials to reduce weight of automotive parts were discussed by Miklos Tisza et al. [7]. Rahmatian et al. [9] investigated double-sided friction stir welding on AA 5083 in terms of various process factors. Das B. et al. [10] employed temperature signal as an approach and experimented with different tool pin profiles. Researchers [2,11,12,13] also discussed and utilized Grey Relational Analysis (GRA) to optimize process parameters for a better weld joint. Microstructural

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analysis using X-ray diffraction (XRD) and Scanning Electron Microscopy(SEM) confirmed that the joint was successful.

Some statistical process parameters were studied by few researchers and evidences were found in the open literature. The Taguchi method of optimization was utilized to optimize process parameters for Al- Mg-Si-Cu) alloys of the Aluminum 5000 and 6000 families for future automotive applications by researchers and researchers have focused on double friction stir welding technique and microstructure analysis at nugget zone [14,15,16,17]. During mechanical testing, Lee et al. [18] produced a hybrid composite material from carbon reinforced polymers on CR 340 plates and discovered epoxy leaks and significant gaps. Marco Parente et al. [11] concluded that TWB (Tailor Welded Blank) formability was reliant on weld line orientation, and its formability was lowered. A pin with a square pin profile was proven to be more effective than any other tool pin profile [19]. Kesharwani et. al. [16] used a Taguchi grey-based technique to multi-objective optimizes two sheet samples of AA 5052-H32 and AA 5754-H22. Experiments were designed using the L9 orthogonal array. Babu K. V., et al. [20] designed an expert system based on Artificial Neural Network (ANN) to analyze deep drawing behavior of Aluminum. Homola et al. [21] suggested the use of laminate plate at areas where lower load is applied to reduce weight in aircrafts. It was observed that lot of work was investigated on FSW but still there is a scope available on developing a novel FSW technique. Hence, using blend of techniques a new method is developed which will improve the mechanical properties of the joint to suit the requirements of the various applications.

Process factors such as tool rotational speed (rpm), worktable translational speed (mm/min), tool geometry, tool material, and tool tilt angle can all be changed, and by optimizing the process parameters, a good welded junction with good tensile strength and percentage elongation can be created. Double sided friction stir welding and multi objective optimization of process parameters are the methodologies which are blended to develop new Friction Stir Welding(FSW) method. The mechanical qualities and formability of this FSW joint are excellent.

Taking cognizance of all above discussions based on research literature availability, it was finalized to use an innovative combination of AA 5182, AA 5754 materials of 1.5 mm thickness to prepare a tailor welded blank and in order to get better mechanical properties of the tailor welded blanks, it was decided to use a novel technique of using double sided fiction stir welding with multi objective optimization of a

few prominent and important process parameters viz. tool rotational speed (rpm), worktable translational speed (mm/min), tool geometry to get better welded joint with better mechanical properties.

2. MATERIAL AND EXPERIMENTAL METHOD

By taking application into consideration, Aluminum-Magnesium Alloys Viz. AA 5182 and AA 5754 are used for experimentation purpose. These materials possess high specific strength, a low weight-to-density ratio, and a moderate strength, ductility and corrosion resistance. As pure Aluminum is scarce in the market, it is frequently mixed

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with Magnesium. They have moderate strength, high ductility, and very good corrosion resistance, wrought Al-Mg alloys are used as structural materials mainly in automobile industries.

Aluminum is soft and brittle by itself, but it can be strengthened by adding minor amounts of copper, magnesium, and silicon to the alloy. The Audi A8, Rolls Royce Phantom, and BMW Z8 all use the 5182 aluminum alloy [21]. Magnesium and manganese are minor components in the 5182 aluminum alloy. The aluminum alloy 5182 is used in the automobile industry to make a variety of parts.5754 Aluminum alloy is a common material in the automotive sector (vehicle doors, moulds, and seals). Magnesium is abundant in the 5000 class of aluminum alloys, which are non-heat treatable. Aluminum is soft and brittle in its pure form, but it can be strengthened by adding minor amounts of magnesium, copper, and silicon [21]. The Al-Mg-Si alloy 5182 is a type of aluminum alloy. It's a moderately strong alloy with good corrosion resistance, weld ability, and cold processing properties. The 5754 aluminum alloy has a medium strength, excellent processing properties, excellent corrosion resistance, weld ability, and ease of processing and forming. AA 5754 is Al-Mg alloy and AA 5754 is widely used in the automotive industry.

Experimentation was carried out on the material chosen and lab testing of base metal is done. The properties of the sample are shown in table 1 as follows:

Table 1. Composition of Elements of Aluminum Sheets

Elements	**AA 5182**		**AA5 754**	
	% Observed	**% Specified**	**% Observed**	**% Specified**
Copper	0.005	0.15 max.	0.004	0.10 max
Magnesium	5.82	4.00/5.00	3.09	2.6
Silicon	0.059	0.20 max	0.199	0.40 max
Iron	0.126	0.35 max	0.492	0.40 max
Manganese	0.449	0.20	0.030	0.5 max
Zinc	0.006	0.25 max.	-	-
Titanium	0.009	0.10 max	-	-
Chromium	0.063	0.30 max	0.179	0.30 max
Aluminum	93.26	93.2 max	95.71	87.1

2.1. TENSILE TEST

Tensile test specimens of the basic material: AA 5182 and AA 5754 sheets are taken according to ASTM E8M standards, as illustrated in fig. 1. Composition of the parent Aluminum alloys is enlisted in Table 1. Tensile tests were performed on AA 5182 and AA 5754 materials. Figure 1 shows the sample sizes obtained which adhere to ASTM E8 M standards. As shown in figure 2, a friction stir welding tool made up of

High speed steel was used. Table 2 lists the mechanical properties found for the basic materials. A 100 kN computerized universal testing machine is employed to carry out the tensile test.

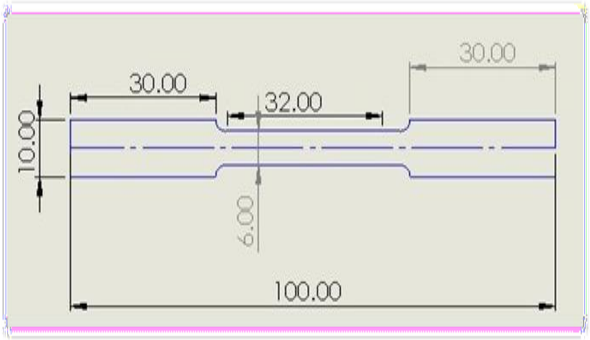

Figure 1. ASTM E8 Tensile Testing Specimen

Figure 2. Friction Stir Welding(FSW)Tool

Table 2. Tensile test result of AA 5182 and AA 5754 sheets

Parameter	AA 5182	AA5754
Specimen Type	Flat	Flat
Cross section area(mm2)	62.850	62.850
Original gauge Length	50	50
Final gauge Length	50	50
Preload(%)	0.2	0.2
Ultimate tensile load(kN)	18.200	14.44
Ultimate Tensile Strength (N/mm2)	209.577	229.752
Displacement at Ultimate load(mm)	12	5.5
Maximum Displacement(mm)	13.2	7.9
Percentage Elongation(%)	22.2	13.240
Breaking Load (kN)	17.240	12.920
Breaking Stress(N/mm2)	274.302	205.667
Yield Load(kN)	11.920	12.120
Yield stress(N/mm2)	189.658	192.840

Electro discharge machining is used to cut 18 samples of size 200 mm x 100 mm from 1.5 mm thick sheets of AA 5182 and AA 5754. Different cross sections of tool pins, such as circular, square, and triangular, are utilized as shown in figure 3. Double-sided friction stir welding is done for making test samples ready for further testing. The advancing side (A.S.) (Al Alloy AA5182) is the side when the tool rotation and welding directions are the same, whereas the retreating side is the opposite (R.S.) (Al alloy AA 5754) (shown in fig. 4). The samples were welded in the rolling direction of the sheet metals throughout the welding process as shown in fig.5 (A and B) for clear understanding about advancing and retreating side.

As indicated in table 3, the Taguchi L_9 orthogonal array is utilized which consist of the factors and levels to apply design of experiments. The various process parameters used during experimentation are shown in table 4. Double Sided Friction Stir Welded (DSFW) samples of200 mm x 100 mm are cut from each of these materials, ASTM E8 specimens for tensile testing are obtained from each of these samples using the process parameters row wise. The results are tabulated in table 4 whereas figure 5 is showing tensile test specimens.

Circular Profile **Square Profile** **Triangular Profile**

Figure 3. Different tool pin profiles

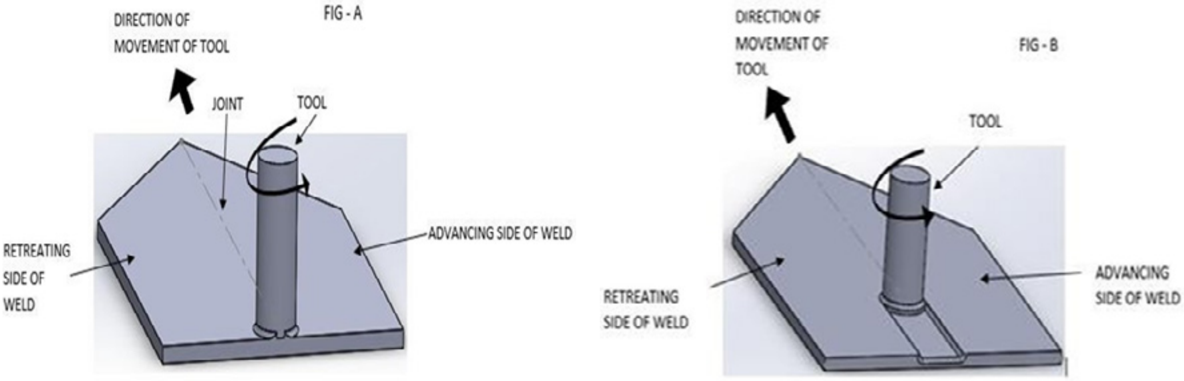

Figure 4 (*A & B*). Advancing and retreating side in Friction Stir Welding

Table 3. Factors and Levels

Sr. No.	RotationalSpeed of tool (rpm)	Worktablefeed (mm/ min.)	Cross SectionalShape ofpin
Level 1	1500	40	Circular
Level 2	1650	50	Triangular
Level 3	1800	60	Square

Figure 5. Tensile test specimen of TWB

Table 4. Taguchi L9 orthogonal input array

Sr.No.	Rotational Speedof tool (rpm) (A)	Work table feed(mm/min.)(B)	Cross sectional shape	FSW designation
1	1500	40	Circular	L_9_1111
2	1500	50	Triangular	L_9_1222
3	1500	60	Square	L_9_1333
4	1650	40	Square	L_9_2123
5	1650	50	Circular	L_9_2231
6	1650	60	Triangular	L_9_2312
7	1800	40	Triangular	L_9_3132
8	1800	50	Square	L_9_3213
9	1800	60	Circular	L_9_3321

3. RESULTS AND DISCUSSIONS

Grey Relational Analysis (GRA) is used in the multi-objective optimization of process parameters, and all samples are prepared using double-sided friction stir welding. The samples with the best ultimate tensile strength and percent elongation are determined.

Experimental readings are normalized in the range from zero to one. The two output parameters, weld strength and ductility values, are dealt with in the grey relational analysis. The results of the tests should be normalized in the range of 0 to 1. Grey relational coefficients and then grey relational grades are computed after normalizing. The higher value of grey relational grade is used to determine the optimal level of each process parameter. The most important controllable element and less important controllable parameters are determined by this technique.

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3.1. GREY RELATIONAL COEFFICIENT CALCULATION

Table 5. GRA Grey Relational Analysis Data Set

(I) GRA GREY RELATION ANALYSIS

DATA SET

	UTS			% Elongation		
SR.NO.	A	B	C	D	E	F
1	*243.716*	*268.11*	*238.47*	*5.87*	*3.33*	*5.33*
2	*51.667*	*21.333*	*88.667*	*0.83*	*1.13*	*2.66*
3	*98.333*	*10.889*	*90.367*	*1.14*	*2.31*	*2.65*
4	*146.667*	*160.78*	*208.743*	*3.56*	*3.12*	*4.01*
5	*222.556*	*182.89*	*73.446*	*3.43*	*2.71*	*0.61*
6	*234.754*	*186.44*	*237.333*	*0.88*	*4.35*	*10.53*
7	*124.778*	*241.89*	*75.956*	*2.04*	*10.86*	*11.8*
8	*157.444*	*233.11*	*61.222*	*2.34*	*10.32*	*0.28*
9	*192.222*	*235.22*	*233.889*	*2.62*	*8.38*	*8.62*

Table 5 is giving the experimental results obtained. Three such sets of readings of Ultimate Tensile strength and % elongation corresponding to the set of parameters used sequentially from Taguchi L9 orthogonal input array(table 4) are shown in table no.5.

Table 6. Normalized data

A	B	C	D	E	F
1.0000	*1.0000*	*1.000*	*1.0000*	*0.2261*	*0.4384*
0.0000	*0.040*	*0.1548*	*0.0000*	*0.0000*	*0.2066*
0.2430	*0.000*	*0.1644*	*0.0615*	*0.1213*	*0.2057*
0.4947	*0.582*	*0.8323*	*0.5417*	*0.2045*	*0.3238*
0.8898	*0.668*	*0.0690*	*0.5159*	*0.1624*	*0.0286*
0.9533	*0.682*	*0.9936*	*0.0099*	*0.3309*	*0.8898*
0.3807	*0.898*	*0.0831*	*0.2401*	*1.0000*	*1.0000*
0.5508	*0.863*	*0.0000*	*0.2996*	*0.9445*	*0.0000*
0.7319	*0.872*	*0.9742*	*0.3552*	*0.7451*	*0.7240*

Table 6 indicates the normalized values. Both ultimate tensile strength and % elongation are better if they are larger. Normalization values are obtained using formula with the help of data available from table 5.

$$v0_ik = 1 - \frac{max\,.\,x0_i(k) - x0_i(k)}{maxx0_i(k) - min\,.\,x0_i(k)} \qquad (1)$$

Here, k = 1 to n and k = 1 to n and i =trial number which is 1 to 9. n = performance characteristic, y=value in normalized data table, x=value from table 1

Table 7. Deviation sequence

A	B	C	D	E	F
0.0000	0.0000	0.0000	0.0000	0.7739	0.5616
1.0000	0.9594	0.8452	1.0000	1.0000	0.7934
0.7570	1.0000	0.8356	0.9385	0.8787	0.7943
0.5053	0.4173	0.1677	0.4583	0.7955	0.6762
0.1102	0.3313	0.9310	0.4841	0.8376	0.9714
0.0467	0.3175	0.0064	0.9901	0.6691	0.1102
0.6193	0.1019	0.9169	0.7599	0.0000	0.0000
0.4492	0.1361	1.0000	0.7004	0.0555	1.0000
0.2681	0.1279	0.0258	0.6448	0.2549	0.2760

Deviation sequence in Table 7 is obtained by formula,

$$Z0_i k = max\,.\,y0_i k \qquad (2)$$

Z=Value in deviation sequence table 7, y=value in normalized data table, k = 1 to n and i =trial numberwhich is 1 to 9. n = performance characteristic

Table 8. Grey relation coefficient

Grey relation coefficient					
1.0000	1.0000	1.0000	1.0000	0.3925	0.4710
0.3333	0.3426	0.3717	0.3333	0.3333	0.3866
0.3978	0.3333	0.3744	0.3476	0.3627	0.3863
0.4973	0.5451	0.7488	0.5217	0.3860	0.4251
0.8194	0.6015	0.3494	0.5081	0.3738	0.3398
0.9146	0.6116	0.9873	0.3356	0.4277	0.8193
0.4467	0.8306	0.3529	0.3969	1.0000	1.0000
0.5267	0.7861	0.3333	0.4165	0.9001	0.3333
0.6509	0.7964	0.9509	0.4367	0.6624	0.6443

Grey relation coefficient is calculated by following formula

$$u0_i k = \frac{min\,.\,z0_i k + 0.5(max\,.\,z0_i k)}{z0_i k + 0.5(max\,.\,z0_i k)} \qquad (3)$$

Here, u=values of grey relation coefficients. Z=Value in deviation sequence table 7. y=value in normalized data table, k = 1 to n and i =trial number which is 1 to 9. n = performance characteristic

Table 9. Grey Relational Grade

(GRG) Grey Relational Grade	Rank
0.8106	*1*
0.3501	*9*
0.3670	*8*
0.5207	*6*
0.4987	*7*
0.6827	*3*
0.6712	*4*
0.5494	*5*
0.6903	*2*

Grey relational grade is obtained by taking average of all grey relational coefficients for a particular set of parameters. The process parameters that correspond to the greater value of grey relational grade are found to be optimal. [20]

The analysis is done on a cutting-edge welding method. Tool rotational speed, worktable translational speed, and tool pin geometry were chosen as process parameters for multi-objective optimization. The ultimate tensile strength and percent elongation are two essential tensile test results that have been calculated to determine the utility of these Aluminum alloys in terms of strength and ductility. Whereas the other characteristics of the welded joints like micro grain structure, distortion etc. are out of scope of this article.

- Using grey relational analysis, it was discovered that using **tool rotational speed of 1500 rpm, worktable translational speed of 40 mm/min, circular tool pin profile, and double sided friction stir welding, the maximum ultimate tensile strength obtained was 268.11 N/mm2 and the maximum percent elongation was 5.87 %.**
- The reason behind getting **92.73% weld joint efficiency as compared with the base metals** is due to proper intermixing of the material at the joint due to optimized process parameters and due to double sided friction stir welding. The material reaches everywhere leaving no space for oxide formation.
- **The basic metals AA 5182 and AA 5754 have ultimate tensile strengths of 289.58 N/mm2 and 220.75 N/mm2, respectively.**
- So, using double sided friction stir welding and optimizing the critical process parameters, such as tool rotational speed, tool pin profile, and welding speed, substantial strength and percentage elongation of custom welded blanks could be accomplished.

4. CONCLUSION

- By using double sided friction stir welding for joining the dissimilar materials the harder material was kept on advancing side. The prominent parameters chosen in this experimentation were tool rotational speed, welding speed and tool geometry. **Tool rotational speed range was 1500 rpm, 1650 rpm and 1800 rpm. The worktable feed values chosen were 40mm/min., 50 mm/min.,60mm/min.**
- At the nugget zone, the mechanical properties are grossly varying as compared to the other zones, viz. thermos mechanically affected zone, heat affected zone and parent metal zone.
- While **the tool profiles chosen were circular, square, triangular with tool material as HSS. Taguchi grey relational analysis** was chosen to find out the optimized process parameters. Weld strength and ductility values were the output parameters used in GRA, it was found that **tool rotational speed of 1500 rpm, worktable translational speed of 40mm/min., circular tool pin profile were found to be the best process parameters when double friction stir welding was employed.**
- **Further, for the tailor welded blank, the maximum weld strength i.e. tensile strength obtained was 268.11 N/mm2which is 92.73% and the ductility i.e. maximum percentage elongation was 44% compared to base metal.**
- Double sided welding ensures that there are no voids at the joint and the new stirred material is leaving no voids at the nugget zone and optimized process parameters ensure that the welding at the nugget zone is best possible with the optimized process parameters.
- This novel blended technique of multi objective optimization of prominent process parameters and use of double sided friction stir welding with harder material on advancing side of the tool can overcome the usual metallurgical problems.
- Tailor welded blanks can give a better welded joint as the intermixing of the material is proper at the nugget zone with this technique and oxide formation associated with brittleness at the joint is also significantly low. Tunnel defect due to improper heat generation, cavity formation due to uneven mixing of the material, oxide formation at the joint is reduced to provide weld joint.

Further, Electron Backscatter Diffraction (EBSD) is proposed to check the micro structure for analysis of lesser ductility which will be the area of Industrial interest.

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