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Experimental Investigation of Mechanical Properties And Morphological Studies on Friction Stir Welded Aluminum 2024 Alloy

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Abstract

In this research work, some important investigations were carried out to find out the changes in the macro, microstructures and mechanical properties of the Aluminum 2024 alloy. It is clearly understood through experimentation that friction stir welded components exhibits remarkable morphological and mechanical properties with proper selection of tool geometry, rotational speeds and feeds which greatly influence the weld quality and the weld strength . The present trialing uses taper cylindrical tool pin profile with different process parameter values under constant axial load of 3 kN were considered. Further the study reveals that tool rotational speed of 1000 rpm, feed rate of 30 mm /min are best suitable for the selected work material which produces tensile strength of 300MPa and high yield strength of 280MPa with parent metal along with marginal tunnel defect.

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Keywords: Friction stir welding, tensile strength, tool profile, tunnel defect, feed, axial load, speed;

1. Introduction

Friction stir welding (FSW) is an innovative joining process which produces no fumes and no filler material is used. It is a environment friendly technique regarded as Green Welding. FSW process is used to join several metal alloys such as aluminum, copper, magnesium, zinc, steels, and titanium. This sometimes produces a weld that is stronger than the base material and is a solid-state joining process, where metal is not melted but the joint is obtained by frictional heat produced when a specially designed tool that rotates on to the work piece surface. The parts must be clamped onto a backing bar in a manner that prevents the abutting joint faces from being forced apart or in any other way moved out of position. The main advantage of the process is that the welding takes place without melting the base metal, thereby eliminating the welding defects like porosity, cracks etc in the welded joints.

Frictional heat is generated between the tool and wok material causing the work pieces to soften without reaching the melting point, and then mechanically intermixes the two pieces of metal at the place of joint, further softened due

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to the elevated temperature, joined using mechanical pressure, applied by the tool. This leaves a solid phase bond between the two pieces. As melting does not occur and joining takes place below the melting temperature of the material, a high-quality weld is created. This characteristic greatly reduces the ill effects of high heat input, including distortion, and eliminating solidification defects. The schematic diagram of the FSW process is shown in Fig 1.

2. Literature review

C.Vidal and V. Infante [2] optimized the friction stir welding process parameters for improving mechanical behavior of aeronautic aluminum alloy joints with minimum cost and time (AA2024-T351). The vertical downward forging force (890 Kg), tool travel speed (308 mm/min), and probe length (4.17 mm) are considered parameters for optimization using Taguchi and ANOVA method to find out the tensile strength, bending strength and hardness. They found that through Taguchi method probe length is the most significant parameter affects 42.68 % to the Tensile Strength and the tool travel speed is the most important parameter affecting 45.31% to the Bending strength and the 53.08% to the hardness.

A. Astarita et al. [3] conducted the experiment to study the forces acting on the tool in all three directions during friction stir welding of AA 2024 T3 sheets. In this principal process parameters are tool welding speed and tool rotational speed. They affirm that there is a correlation between the forces and the grain size, in particular with the extension of the heat-affected zone. Forces acting along the axis parallel to the tool are actually greater than those acting along welding direction. Moreover the joints produced were free of defects. It was observed that there is no any correlation between forces and grains dimension. In the nugget zone, a fine and equiaxic microstructure was observed. In the HAZ, larger grain with an elongated shape was observed. But there is a correlation between the measured forces and the extension of the heat-affected zone. In particular, it was observed that the extension of the HAZ decreases as the forces increases.

Koilraj et al.[4] in their work, optimization of process parameters of friction stir welding of dissimilar aluminum alloys (copper, aluminum and magnesium alloys)using Taguchi technique (Taguchi L16 orthogonal design of experiments), considered parameters rotational speed, traverse speed, tool geometry and ratio between tool and shoulder diameter and pin diameter for optimization to investigate tensile strength of the joint. The results were analyzed with the help of analysis of variance (ANOVA) and concluded that optimum levels of tool rotational speed is 700 rpm , traverse speed is 15mm/min , ratio between tool shoulder diameter and pin diameter is 3, pin tool profile is cylindrical threaded and finally friction stir welding produces satisfactory butt welds.

In this paper, Aluminum 2024 alloy was taken as the base metal and conducted the experiments to investigate some important mechanical properties such as tensile strength, yield strength, hardness and microstructure under different tool speeds, feeds and constant axial load using of taper cylindrical tool pin profile.

3. Experimental work

Looking into the characteristics like good machinability, surface finish capabilities, adequate workability, largely superseded 2017 for structural applications and used in manufacturing parts such as aircraft fittings, gears and shafts, bolts, clock parts, computer parts, couplings, fuse parts, hydraulic valve bodies, missile parts, munitions, nuts, pistons, rectifier parts, worm gears, fastening devices, veterinary and orthopedic equipment, structures etc. The Aluminum 2024 alloy is taken as the parent material for investigating its properties such as tensile strength, yield strength, percentage elongation, hardness, macrostructure and microstructure.

In this work, four specimens of Aluminum 2024 alloy of each plate having 100 mm length, 50 mm width and 5 mm thickness (100x50x5 mm), prepared by machining, cutting and milling processes is considered for investigation. The chemical compositions and mechanical properties of Aluminum 2024 alloy are listed in Table 1 and 2.The Aluminum 2024 alloy flat plates were firmly secured in their position with the help of mechanical clamps and the tool is held rigidly in its position as shown in the Fig 2.

The Friction Stir Welding of Aluminum 2024 alloy was performed using a semiautomatic FSW machine with a table size of 810 X 400 mm and a spindle speed ranging from 20 – 2000 rpm with a feed range of 0.25 to 500 mm/min. This machine has a 10hp motor and produces of power of 5 kW which can provide a 3 ton mechanical linear axial force in the vertical direction. Additionally, the machine has a 510 mm travel distance along the X axis, 400 mm along the Y axis and 400 mm with respect to the Z axis.

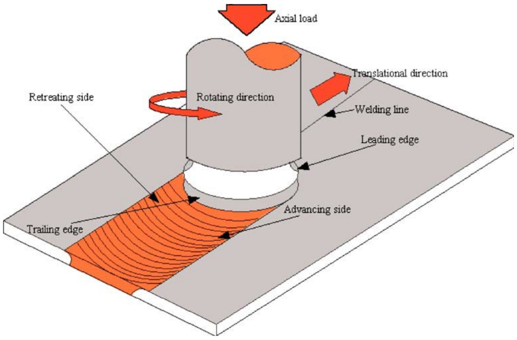


Fig 1 : Schematic diagram of the FSW process [1]

Fig 2: Photographic of Al 2024 alloy fixed in the FSW machine

Table 1: Chemical composition of Aluminum 2024 alloy

Alloy	Composition wt %								
Aluminum	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Al
2024	0.1	3.8 to 4.9	0.5	1.2 to 1.8	0.3 to 0.9	0.5	0.15	0.25	Balance

Table 2: Mechanical properties of Aluminum 2024

Alloy	Tensile Strength (MPa)	Yield Strength (MPa)	Percentage Elongation
Aluminum 2024	400	276	10

3.1 Tool Material Selection

In FSW, the tool material is very important factor in determining the quality of the welded joints being produced. The selection of the tool material is dependent on the material of the parent metal to be welded for the different combinations of rotational speeds and feed rates. A Non-consumable tool made of steel which is known as D2 steel is taken as the tool material for the present work due to the reason that the alloy is Cold Work with high-carbon, high-chromium, air-hardening tool steel that is characterized by a relatively high attainable hardness and numerous, large, chromium-rich alloy carbides in the microstructure. It is heat treatable and will offer hardness in the range 55-62 HRC, and is machinable in the annealed condition. These carbides provide good resistance to wear from sliding contact with other metals and abrasive materials. Although other steels with improved toughness or improved wear resistance are available, D2 provides an effective combination of wear resistance and toughness, tool performance, price, and a wide variety of product forms. The details of heat treatment and chemical composition of D2 tool steel are presented in Table 3 and 4.

Table 3: Chemical Composition of D2 tool steel

Composition wt %					
C	Mn	Si	Cr	Mo	V
1.50	0.30	0.30	12.00	0.75	0.90

Table 4: Heat Treatment Details of D2 tool steel

Annealing (Slow cooling)	Quenchent	Tempering(Air cooling)	Quenched & Tempered (hrc)
Anneal at 871°C to 898°C followed by slow furnace cooling at 4 $^{\circ}$C per hour or less	Air or Oil	150-200°C	62

3.2 Design of Tool Pin Profile

The tool pin profile and its geometry are found to play a significant role in determining the generation of heat and plastic flow during welding. Moreover, the uniformity of the welded joint produced and the soundness of the good quality of weld are directly dependant on the tool pin profiles and its geometry. The shoulder generally performs two functions generating larger amount of heat and preventing the plasticized material from escaping the surface of the work piece. The pin profile has been found to have a major input on the flow of materials in the stir zone during the process. The tool pin geometries selected for the purpose is cylindrical taper and its specifications, dimensions are shown in Table 5. The Photographic view of tool is shown in Fig 3.

Fig 3: Photographic view Taper Cylindrical Tool

Fig 4: Sample Specimens - Welded Joints

3.3 Selection of Process Parameters

The key parameters in FSW that control the quality of the weld are: (i) the axial force, (ii) tool geometry and tool tilt angle (iii) rotation speed, (iv) traverse speed. Each and every process parameter has its own significance on welding and its quality. In the present work, three process parameters 1. tool rotational speed, 2. welding speed / feed rate and 3. axial force. are considered for the investigation of mechanical properties and morphology of the Aluminum 2024 alloy. The first specimen is welded at tool rotational speed of 900 rpm, feed rate or welding speed 20 mm/min, and axial force of 3 kN, similarly other three specimens are welded with different values of process parameters which are considered based on the previous literatures and it is tabulated in the Table 6.

Table 5: Tool pin specifications & dimensions

Shape of the Tool pin profile	Inner Shoulder Diameter D (mm)	Pin Length L,(mm)	Major Pin Diameter (mm)	Minor Pin Diameter d, (mm)	D/d ratio of the tool
Cylindrical Taper	20	4.8	6	3	4

Table 6: Process Parameters and its values

Process Parameters	Aluminum 2024 Alloy Work pieces (Specimens)			
	Specimen 1	Specimen 2	Specimen 3	Specimen 4
Tool rotational speed (rpm)	900	1000	1100	1200
Feed rate (mm/min)	20	30	40	10
Axial Load (kN)	3	3	3	3

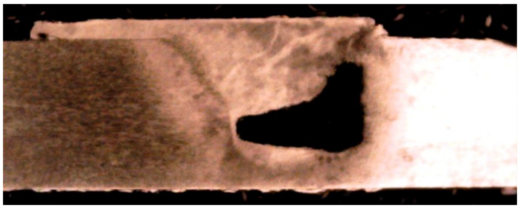
4. Results And Discussions

4.1. Appearance of joints

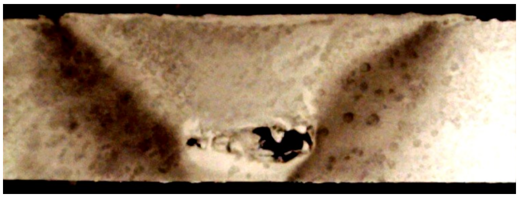
The photographs of the welded joints of four samples are shown in Fig 4. The joints are successfully produced using the friction stir welding technique with the help of the D2 steel tool having cylindrical taper pin.

4.2. Macrostructure of the FSW joints

The top surface of the welded joints seemed to be free from visible defects. However, the cross sections of some of the welded specimens are found to be present with tunnel defects in the various sections of the welded zone. Under the macroscopic examinations, defects were observed when analyzed under the low magnification (20X) using the optical microscope. It is observed that the sample 1 and 4 which are welded at the tool rotational speed of 900 rpm and 1200 rpm and feed rate of 20 mm/minute and 10 mm /minute respectively have shown the larger size tunnel when compared with the sample 2 and 3 which are welded at the 1000 rpm and 1100 rpm and feed rate of 30mm/minute and 40 mm/minute respectively. The macroscopic images are shown in Fig 5.

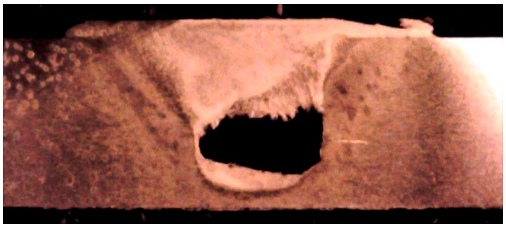


Sample 1



Sample 2

Sample 3



Sample 4

Fig 5: Macro structure of the Specimens showing varying sizes of tunnel defect

4.3. Microstructure of the FSW joints

Microstructure of the four samples of Aluminum 2024 alloy is studied using De-Winter Inverted Trinocular Metallurgical Microscope having Magnification range 50X to 1000X. The micro studies are conducted with the magnification of 100X and using Hydrofluoric acid solution as an etchant. The microstructure study reveals the following observations.

- The parent metal showed that precipitation of Copper-Aluminum in primary alpha aluminum solid solution as shown in Fig 6(a).
- In the Heat affected Zone (HAZ) the precipitates of Copper-Aluminum has dissolved due to heat and re precipitated in large cluster particles. The heat affected zone shows large grains as shown in Fig 6 (b) .

- The Nugget Zone shows, fine fragmented particles of eutectic constituents in primary alpha aluminum solid solution as the heat of the process is dissolved as shown in Fig 6 (c).
- In TMAZ(Thermo Mechanically Affected zone) shows the grain orientation has changed due to heat and the stress of the process and resulting in the onion ring formation as shown in Fig 6 (d).
- Finally Nugget – Parent interface showed that the material attained super plasticity due to which grains have oriented along the direction of the tool as shown in Fig 6 (e) and (f).

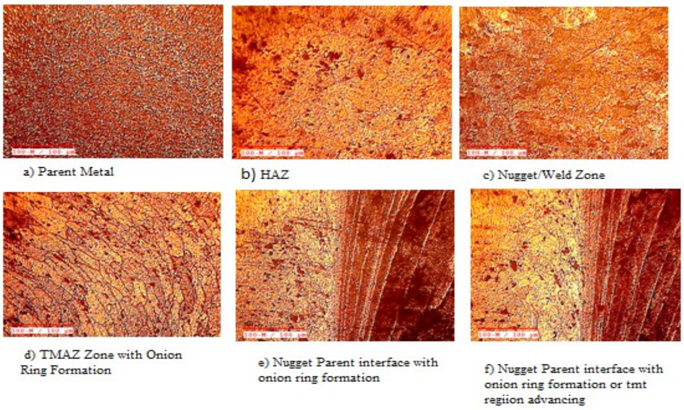


Fig 6 : Microimages of the Aluminum 2024 alloy

5. Hardness

The hardness test is performed using the machine Micro Vickers Hardness Tester having testing load range of 10 grams to 1 Kg Load and vernier caliper least count of 0.01mm. The test is performed at the four different places namely parent metal advancing side , HAZ, Nugget zone and Parent metal retreating side. At each places three different readings are taken and all the tests are performed on all the four specimens. The applied load is 0.5kg and dwell time is 10s. The results of the hardness values are shown in Fig 7 with reference to the distance from the weld centre, the vertical centre line shows the hardness values obtained and the horizontal line shows the distances in millimetre and S1, S2, S3 and S4 represents the four different specimens of the aluminium 2024 alloy.

Hardness in the weld zone is slightly higher when compared to Thermo-mechanically affected zone and Heat affected zone (HAZ) which is attributable to small grain size. Decreasing trend of hardness in TMAZ is due to dissolution of precipitates and lower hardness is pronounced in the Heat affected zone (HAZ) due to coarsening of precipitates and the observations are in accordance with the previous researcher [5].

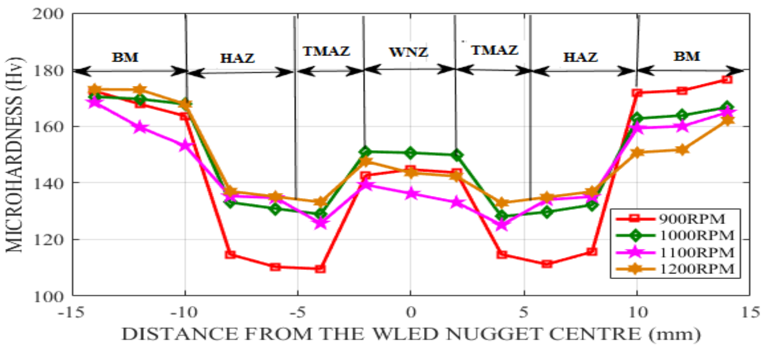


Fig 7: Experiment results of hardness values

5. Mechanical Properties

In order to investigate the mechanical properties of the friction stir welded specimens of Aluminium 2024 alloy, all the four specimens were cut using Wire cut EDM to obtain accuracy for the tensile specimen. One of the specimens cut for the tensile test is shown in Figure 8. The tests were conducted as per the standard procedures prescribed by the American Society for Testing of Materials (ASTM), specimen preparation is also as per standard guidelines.

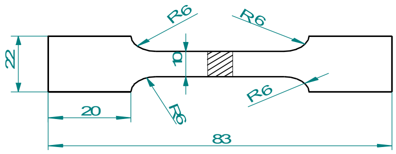


Fig 8: Tensile specimen prepared as per ASTM

The test lengths of specimens were cut along the processed direction. The photographs of the same are shown in Fig 9 and the cut tensile test specimens were used to evaluate the tensile strength, yield strength and % elongation of the friction stir welded Aluminum 2024 alloy plates. The tensile test is performed on a Universal testing machine having capacity of Maximum 5 ton and the prepared tensile specimens were inspected and loaded at the rate of 1kN/min as per the ASTM guidelines and the photographic view of the broken tensile specimens is shown in Fig 10.

From the above results it is evident that the specimen 2 is having high tensile strength, high yield strength and relative percentage elongation is 4 this reflects better results in terms of mechanical properties when compared with other specimens. From this it can be understood that to achieve high joint strength, the process parameters such as tool rotation speed of 1000 rpm and feed rate of 30 mm/min are appropriate to weld the Aluminum 2024 alloy. The ultimate tensile strength obtained by this joint specimen is 300 MPa which is approximately 75% of the tensile strength of the work material which has ultimate tensile strength of 400 MPa. Moreover, the yield strength of the joint is 280 MPa which is greater than the parent metal by 1% (276 MPa) that is 101%. Finally percentage of elongation for this joint is 4 % which is 40% than that of the parent metal. The stress versus strain graph is shown in Fig 11.

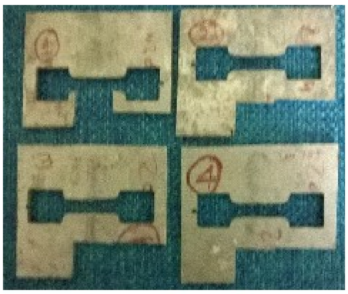


Fig 9: Photographic view of the cut portion of the Aluminium 2024 alloys

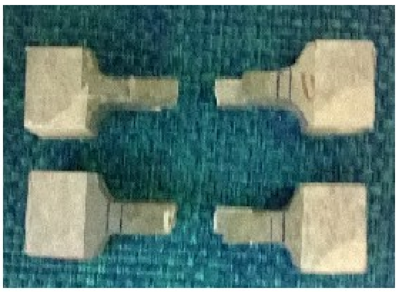


Fig 10 : Photographic view of the broken tensile specimens

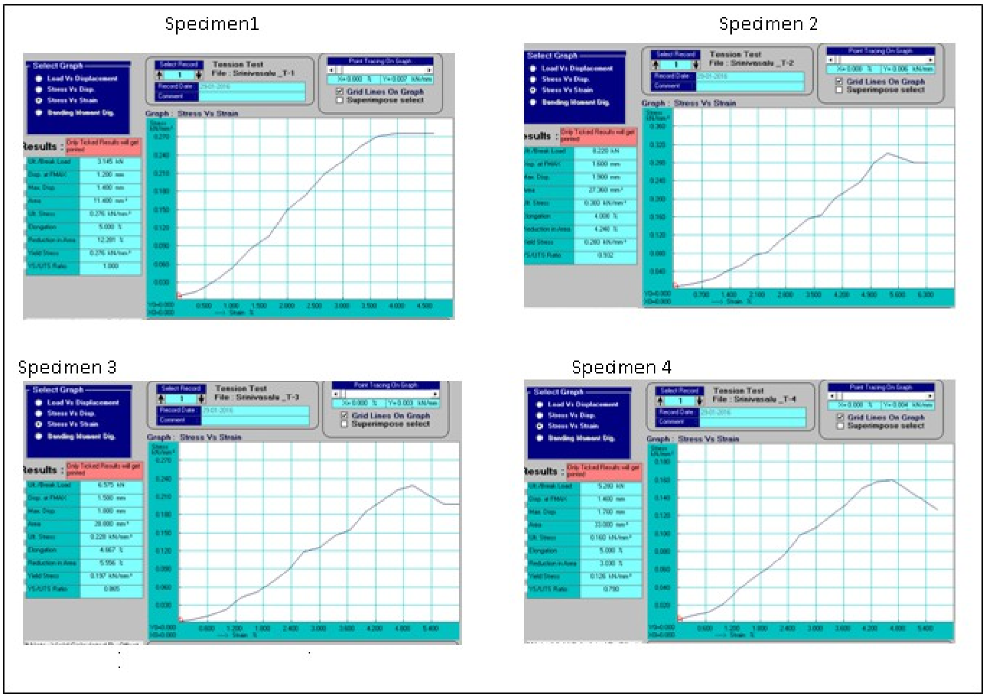


Fig 11: Stress- Strain graph generated during tensile test of the specimen

6. Conclusions

In this research work, some important investigations were carried out to find out the changes in the macro, microstructures and mechanical properties of the Aluminum 2024 alloy by using taper cylindrical tool pin profiles with different process parameter values under constant axial load of 3 kN. It is clearly understood through experimentation that friction stir welded components exhibits remarkable morphological and mechanical properties. The proper selection of tool rotational speeds and feeds will have greater impact on the weld quality and the weld strength. The following concluding remarks can be made from this study.

Primarily macro structure study reveals that low tool rotational speed with high feeds produce tunnel defect of larger size as compared to welds produced at high tool rotational speed and high feeds. Second, the welded joint shows 75% of parent metal tensile strength, high yield strength of 101% and relative percentage elongation is 4 for the specimen 2 when compared with other specimens and the tool rotational speed of 1000 rpm and feed rate of 30 mm /min are best suitable for the selected work material.

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