

Concomitant Outcomes due to the Alterations of Process Parameters During the Friction Stir Welding of T-Joint Between Dissimilar Aluminium Alloys

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Abstract

Dissimilar Friction Stir Welded T-joints gives auxiliary strength to engineering structures, keeping insignificant body weight. Due to the stronger material being away from the heat source, the T-joint between AA8011 and AA5754 is very vulnerable to formation of defects which results in lower tensile strength along the skin and stringer. In this paper, two aluminium alloys, namely AA5754 and AA8011 were friction stir welded in the T-joint configuration, and the roles of welding parameters such as the tool transverse speed, tool rotational speed, and tool shoulder diameter on the tensile strength along skin and stringer was analyzed and discussed. The relative importance of the three process parameters was also analyzed. The tool shoulder diameter is found to be the most dominant factor for the strength along the skin, whereas, tool transverse speed is found to be the most important for the strength along stringer.

1. Introduction

Friction stir welding (FSW) is a recent welding technique developed and patented by W. Thomas and his colleagues in 1991 at the welding institute, Cambridge UK [1]. Leading industries, such as aircraft and aerospace sectors require joining of complex profiles as skin and stringer for the reduction in weight and enhanced mechanical properties. Since the commencement of the aerospace industry, designers have striven to attain a reduction in weight [2]. This drives a wide range of applications of aluminium alloys for wings, fuselage, and supporting structures in aircraft and transport industries (stiffened panels in railroads, car bodies, airframe structures, ship hulls, etc.). Some applications require joining of skin having high toughness and stringers having high strength in T-joint or corner weld configuration to create a strong supporting arrangement [1].

Since FSW is a solid-state welding technology, the melting of base materials is avoided, which eliminates several metallurgical defects and prevents the release of toxic fumes [3]. FSW is becoming a promising welding technique in transport and building industries to yield distortion-free welds. T-joints manufactured with FSW are produced with a specially designed tool having a pin that is inserted in the skin which results in localized backward and forward extrusion process of the flange material to reach the tool shoulder and penetrate up to the stringer [4]. The tool shoulder diameter, rotation and traverse speed determine the amount of heat generation and are responsible for the plastic flow of material from the Advancing side (AS) to the retreating side (RS) [5]. It has been reported that 86% of heat is generated by the friction between tool shoulder and part surface and rest due to the tool pin friction and plastic

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strain [6]. The tool peripheral velocity and traverse speed vectors have the same direction in AS, however these are opposite in the RS.

Research work published on T-joints fabricated by FSW is much scarce in comparison to the butt joints. Acerra et al. [3] conducted a series of experimental trials on T-joints of dissimilar materials to obtain optimum process parameters to yield sound welds, and reported that tools with large diameter required to provide the heat necessary for softening. When compared to butt joints, FSW of T-joints poses different challenges. Tool geometry, adequacy of the clamping, and distribution of heat during the process are some of the major challenges that researchers have explored. Buffa et al. [7] analyzed the material flow in FS welded T-joints by relating the experimental results with numerical simulation. The effect of two different tool profiles on heat distribution was also studied in this work. Zhao et al. [8] investigated the defects and tensile strength of 6013 Al alloy by fabricating T-joints with two different combination methods employing different process parameters. Different combination methods of T-joints as also been discussed in the literature [9-10]. Studies by Silva et al. [11] and Ahmed et al. [12] showed that FSW is a promising welding technique in the fabrication of age-hardened Al alloys panels. Feistauer et al. [13] analyzed the effect of reverse material flow on the microstructure of the T-joint of an Al-Mg alloy. Yang et al. [14] compared the strength of T-joints obtained with a single and double pass by FSW and concluded that peel strength with a double pass is almost twice with that of a single pass. Publications by Erbslöh et al. [15] and Donati et al. [16] have proved the feasibility of FSW in the fabrication of T-joints and have employed the filler material to avoid the defects. Krasnowski et al. [17] investigated the weldability of EN-AW 6082-T6 T-joint by FSW and the mechanical and metallurgical properties of the joint. Fratini et al. [7] examined the FS welded T-joints by FSW of AA2024-T4 and AA6082-T6 alloys and focused on the function of material characteristics of base materials in obtaining the weld. Mechanical analysis on T-joint of AA6082 T6 by FSW was carried out, with a special focus on the influence of rolling direction with respect to welding direction [18]. However, the selection of suitable process parameters is still very challenging in FSW of T-joints as they prominently affect the mechanical and metallurgical properties of the joint. T-joint configuration requires high strength as its area of application includes building structures, ships, aircraft fuselage, and wings, etc. Silva et al. [11] analyzed the FSW process by optimizing the process parameters using the Taguchi L-9 method and reported that tool rotational speed is the most important parameter in determining the mechanical properties of the joint. Also, literature reveals that research published on FSW of T-joints is mostly limited to welding of similar materials. FSW of dissimilar alloys remains challenging with stronger alloy placed as stringer, since softening beneath the skin material becomes difficult [19]. Therefore, the present work examines the role of rotational speed, shoulder diameter and traverse speed on dissimilar T-joints welded using FSW, with the alloy having higher tensile strength being the stringer material.

2. Experimental Procedure

The T-joint by FSW was completed using a specially designed tool on a sturdy vertical milling machine. It requires a properly build clamping fixture to hold the web beneath the skin. In the present study AA8011-H14 (flange/skin) with dimensions 200mmx 70mm x 3mm and AA5754-H24 (web) with dimensions, 200mm x48.6mm x 3mm were welded.

The chemical composition of AA5754 and AA8011 alloys are given in the Table 1 and Table 2, respectively. Mechanical properties of the base materials are given in Table 3. Before welding the plates were cleaned with an organic solvent and dried. The experimental setup employed for the present work is shown in Figure 1. H13 die steel tool was employed to perform the weld. Figure 2 shows the schematic drawing of the FSW tool.



Figure 1: Experimental setup employed for FSW

Table 1: Chemical Composition of AA5754 (wt.%).

Element	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others
Wt.%	Balance	0.25	0.27	0.08	0.39	3.1	0.28	0.2	0.1	<0.15

Table 2: Chemical Composition of AA8011 (Wt.%)

Element	Al	Si	Fe	Mn	Ti	Cu	Pb	Sn	Ti	Zn
Wt.%	Balance	0.67	0.62	0.10	0.02	0.01	0.006	0.016	0.023	<0.010

Table 3: Mechanical properties of the base material (BM).

Al Alloy	AA5754	AA8011
Tensile Strength (MPa)	227.8	137.8
Hardness (HV)	68.4	46

Test specimen were machined using CNC wire electric discharge machine (W-EDM) for tensile testing. The standard metallurgical methodology of polishing and etching was used to prepare the samples macrostructural examination. Tensile testing of the joint along the skin as well as along the stringer was carried on Tensometer, as shown in Figures 3 and 4. Table 4 shows the Taguchi L4 experimental design used in the present study.

Table 4: Process Parameters employed for FSW

Sample No.	RPM	Feed	Shoulder Diameter	Strength	
				Skin	Stringer
1	560	63	18	20.1	34.6
2	560	50	12	51.1	67.9
3	710	50	18	44.1	46.6
4	710	63	12	46.7	8.8

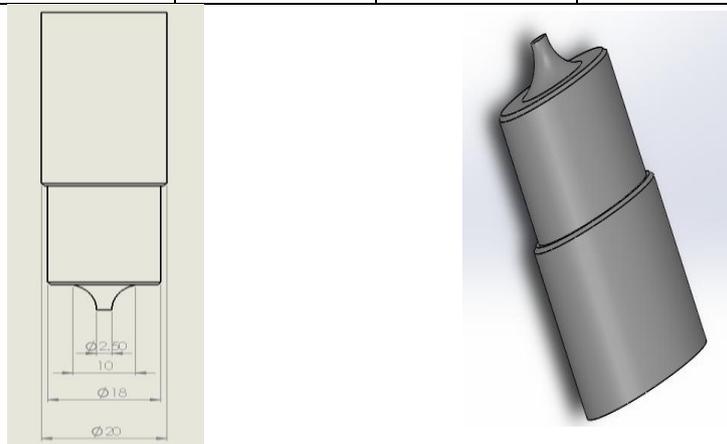


Figure 2: Schematic drawing of tool employed for FSW

To analyze the effect of process parameters i.e., rpm, feed, and shoulder diameter (SD) Taguchi's L-4 method was employed. The signal to noise (S/N) ratio is calculated for each factor level combination and considering larger the better. Using the formula as given below.

$$\frac{S}{N} = -10 \log_{10} \sum ((1/Y^2)/n)$$

where,

n = number of experiments performed on each level

Y = response of given level combination



Figure 3: Fixture used for tensile testing along Skin

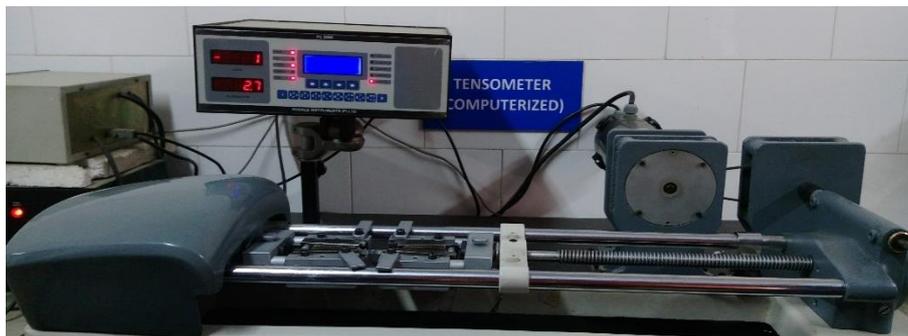


Figure 4: Sample arranged on a computerized tensometer for testing

3. Results and Discussion

The tensile strength along the stringer and skin are most important factors in the dissimilar material T-joints. The T-joints of acceptable strength provide reliable basis for the fabrication of tailor welded blanks (TWB). The tensile testing of regular butt-joints are both normal and simple and has well established standard which provide guidelines and specifications for the testing of joint strength. But, for the testing of strength of the T-joints along the skin and stringers much needed guidelines are still evolving. To test the strength of the t-joints along skin and stringer especial fixtures were prepared and the testing was performed on standard tensometer.

3.1. Tensile Strength

To observe the effects of the main FSW process parameters on the two joint strengths the Taguchi's L4 orthogonal array was used. The measured values of the strengths along the skin and stringer were converted in the S/N ratios (higher the better characteristic). The main effects

plots were plotted and are shown in Figure 5 and Figure 6. There is a significant difference between the strengths of the 8011(softer) and 5754 (stronger), in the present case the 8011 alloy forms the skin and hence receives more heat as it forms an interface with the shoulder. The spinning tool with a tilt causes the stirring which mixes the two materials well. The material mixing of the materials significantly affected by the three chosen FSW parameters. The main effect plots helps in identifying the levels of parameters which gives the value of most desirable or optimized results. The optimum setting of the parameters within the given ranges can be identified by the levels of each factor for which the value of S/N ratio is higher. The Fig 5 reveals that the strength of the skin the rpm at the higher lever and the traverse speed and the shoulder diameter at lower levels represent the higher S/N ratios. Thus the strength of skin is optimum for tool rpm of 710 traverse speed of 50 mm/min and the shoulder diameters of 12 mm. In case of strength of the stringer the optimum values is attained at the tool rpm of 560 traverse speed of 50 mm/min and shoulder diameter 18 mm.

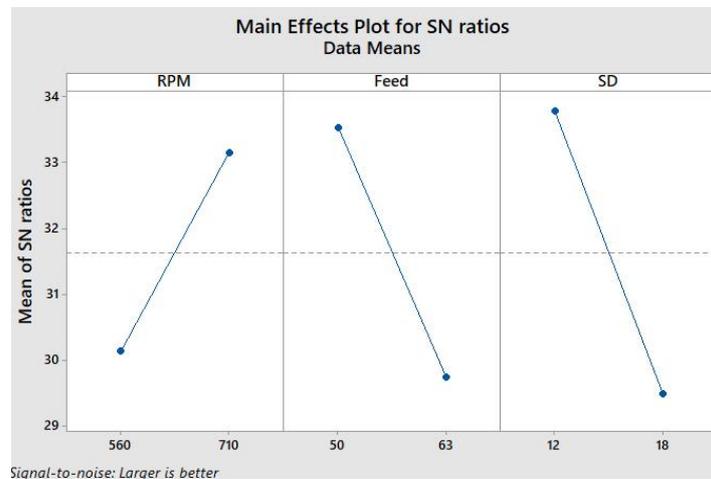


Figure 5: Signal to Noise Ratio VS process parameters in the skin

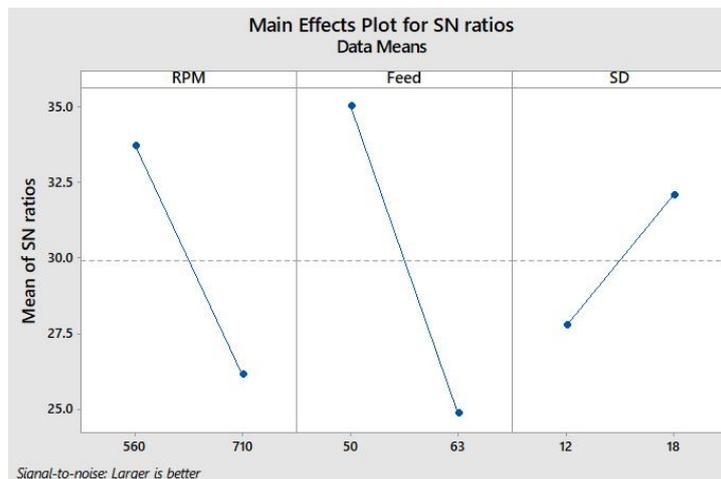


Figure 6: Signal to Noise Ratio VS process parameters in the stringer

In the case of skin, the strength increases with an increase in rotational speed, but the reverse was observed in the case of the stringer. In the former case, it is due to the proper intermixing of softened material at high rotating speed which results in strong metallic bond while in the latter case it may be due the insufficient material flow from the bottom to the top and due to excessive softening of the stringer due to which consolidation process is drastically affected. A low rotational speed generates insufficient heat to produce an effective bond between the two base alloys and with high rotational speed, excessive softening results which

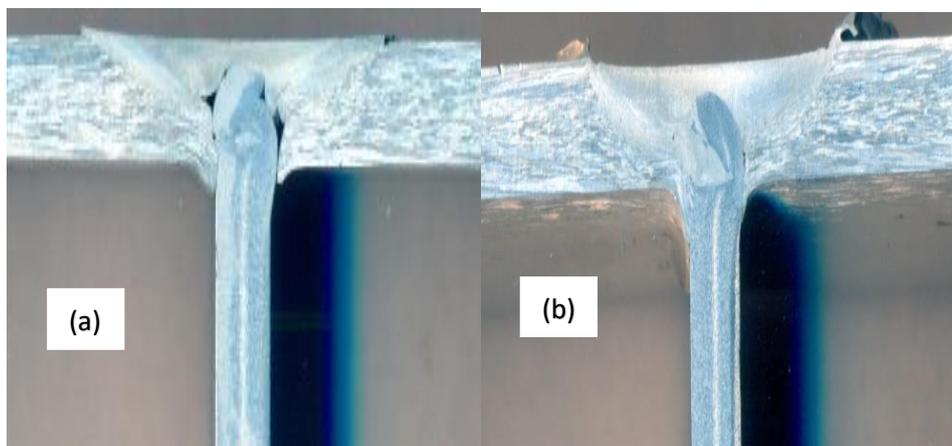
reduces the chance to consolidate the material effectively both reasons leads to a reduction in tensile strength [20].

The tensile strength in the case of skin as well as in stringer decreases with an increase in traverse speed it is due to the insufficient heat generation at a high traverse speed which fails to produce an effective metallic bond. Increasing the traverse speed is accompanied by a reduction in frictional heating, thus reduction in grain, sub-grain sizes, and a reduction in the extent of recovery in the stir zone is commonly observed. Reducing the traverse speed at constant rotational speed results in an increase in frictional heat input per unit length thus affecting the workpiece. This is due to the fact that at low feed rates the workpiece remains under frictional heat for a greater length of time. With increasing shoulder diameter, the tensile strength in the skin decreases while in the case of stringer it increases. In the former case with increasing the SD, the weld flash increases, leading to material deficiency in the cross-section of the weld. In the latter case, the larger shoulder diameter increases the forging action, helps in filling the fillet area effectively thus producing an effective bond between the skin and the stringer alloys.

3.2. Macrostructure

The macrostructures of the weld structures are shown in Fig.7. The well-known zones in FSW weld structure are stir zone (SZ), Thermo-Mechanically Affected Zone (TMAZ), Heat Affected Zone (HAZ) which can be easily demarcated corresponding to skin and stringer. The distinct weld zones possess characteristic properties, grain structures, and grain sizes. SZ experiences Severe Plastic Deformation (SPD) and higher heat generation due to extensive stirring caused by the tool pin which results in dynamic recrystallization.

The induced plastic deformation in the adjoining region of the TMAZ is the result of the lower heat input. HAZ undergoes a thermal cycle that leaves it with grains larger than BM. The narrow weld zones in the stringer part are attributed to the lower heat input at the pin bottom. Due to the varied degree of softening in the materials of stringer and skin, the mixing and stirring is difficult. This is the main cause of tunneling defect being formed during T-joint between two different materials with considerable difference in their strengths. The reason is that reducing the feed rate at constant rotational speed increases friction heating/heat input per unit length affecting the workpiece. This result was also reported in previous works which assumed that as the maximum temperature reached within these feed rates, static grain growth could take place after recrystallization [21].



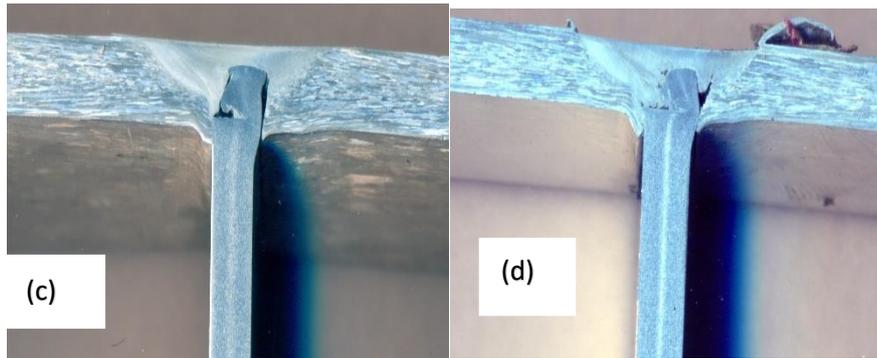


Figure 7: Macrostructures corresponding to (a) Sample 1, (b) Sample 2, (c) Sample 3, and (d) Sample 4.

Tunneling defect has been observed in all the FS welded joints. Lower rotational speed of 560 rpm along with a higher feed rate of 63 mm/min generates insufficient frictional heat and therefore results in improper mixing of the weld materials on AS as well as RS side as shown in Fig. 7a. Decreasing the value of the feed rate to 50 mm/min keeping the rotational speed unchanged, the tunneling defect is seen to have drastically reduced as evident in sample 2.

The presence of significant tunnels on the RS is attributed to the deficient forging effect of the tool shoulder(12mm) as evident in sample 1. This also leads to flash formation and the loss of material and ultimately deteriorates the weld quality. The presence of KB defect in the samples is the result of the insufficient transfer of heat at the interface of skin and stringer. Kissing bond defects are evident in the connection zone of the stringer to the skin. This kind of defect could result in catastrophic failure under both mechanical solicitations; since it could act as a preferential site for crack initiation and propagation.

4. Conclusion

With the assistance of specially designed tool and clamping fixture, T-joint FSW was performed on AA5754 and AA8011 alloys. of the conducted experiments and performed calculations lead to the following conclusions:

1. Feed plays a crucial role in tunnel formation. It is evident that reduction of traverse speed at constant rotational speed resulted in smaller tunnels. For the sake of improved tensile strength, traverse should be kept at a lower value.
2. The optimum weld obtained in the case of skin is having the parameters, 720 rpm, 50 mm/min and 12 mm shoulder diameter while in the case of stringer it is obtained at 560 rpm, 50 mm/min, and 18 mm shoulder diameter.

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