Sustainable Processing of Dissimilar Aluminium Alloy Joints by Friction Stir Welding

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Abstract. Friction stir welding is one of the unique solid state welding technique that is fast gaining importance because of its excellent properties pertaining to the strength, wear, hardness and better joining capabilities. The friction stir welding technique is effectively used in this research to join 5 mm thick dissimilar aluminium alloys of AA 7075 and AA 5052 grade. The friction stir welding joints are obtained by using three different tool profiles viz., straight cylinder, taper cylinder, and straight triangular at a speed of 800, 1000, 1200 rpm and a feed rate of 100, 120, 140 mm/min. The experiments are designed based on L9 orthogonal array considering Taguchi techniques. From the experimental results, the process methodology is validated and the outcomes of the experiment are considered for fabrication of strong joints. The design and optimization of the process has led to better process control and thereby extended its scope for the use of the optimized process parameters for joining dissimilar aluminium alloys in real time engineering applications with sustained methodologies involving reduced dwell time and optimized friction forces and torque during the friction stir welding of dissimilar aluminium alloys.

Keywords: Friction stir welding, Dissimilar aluminum alloys, AA 5052, AA 7075

1. Introduction:
Friction stir welding (FSW) is the solid-state welding process, in which the joining of work pieces can be done by using non consumable tool, which helps to soften the metal by generating a heat due to friction between rotating tool and work piece. When the tool is rotating on the work piece, it will plastically deform the material and result in a strong joint. FSW process is fast gaining significance in welding of Aluminium and its alloys, especially in aerospace and automobile components [1–4].

AA 7xxx and AA 5xxx are light metal alloys which are most commonly used in various structural applications, especially in the field of aerospace, marine and automobile industries. When these materials are used to fabricate different structural components, the total weight will be decreased. The joining of dissimilar aluminum alloys by using conventional fusion welding technique results in the formation of intermetallic compounds and various welding related
defects [5] due to the generation of high temperature. Formation of solidification cracks in the aluminum alloy is a common defect in fusion welding of aluminum alloys due to variation in the weld metal composition. The composition of base metal, filler metal and amount of dilution is very important to reduce the formation of solidification cracking. Henceforth, FSW process can provide the solutions to these types of defects [6, 7]. Further, the process parameters have a major effect on the outcomes of the results in the FSW process.

2. Materials and Methods

2.1. Work Piece Material
The process of friction stir welding is carried out on dissimilar alloys of aluminium, viz., AA 7075 and AA 5052, the composition of the alloys selected for the present work is given in Table 1. The work piece is cut into a required size of 170 x 60 x 5 mm, depending upon the available fixture dimensions to hold the work piece.

| Elements (Wt. %) | Al | Zn | Mn | Si | Cu | Fe | Mg | Ti | Cr | Others |
|-----------------|----|----|----|----|----|----|----|----|----|--------|
| Al7075          | Bal.| 5.8| 0.2| 0.4| 1.6| 0.4| 2.4| 0.1| 0.25| 0.14   |
| Al5052          | Bal.| 0.1| 0.1| 0.45| 0.1| 0.35| 2.6| -   | 0.2| 0.15   |

AA 7075, aluminium alloy is selected for the present work, since it exhibits high strength, fracture toughness and resistance to corrosion which is the basic attribute for its use in aerospace structures, while AA 5052 is an aluminium alloy having magnesium as the major alloying element with better strength, corrosion resistance and weldability that is the major factor for its selection in present work to optimize the process parameters of the FSW for plate structures especially having its wide scope in aerospace components.

2.2. Tool Material
The friction stir welding is carried out by using a typical non consumable tool made up of H13 tool steel with the hardness 55 HRC. The specification of tool is shown in Table 2. In the present research work, three pin profiles viz., cylindrical, cylindrical taper, and triangular have been considered.

| Tool shouldor | 20 mm (flat surface) |
|---------------|-----------------------|
| Tool pin configuration | Cylindrical, Cylindrical taper, and Triangular |
| Pin length | 4.8 mm |
| Cylindrical | D = 5 mm |
| Triangular | L = 5 mm |
| Cylindrical (Taper) | D = 5 mm, d = 4 mm |

2.3. Experimental Methods
Aluminium AA 7075 and Aluminium AA 5052 alloys are welded together by friction stir welding process on an ETA make 10T model horizontal FSW machine as shown in Figure 1. The process is carried out in accordance with the Design of Experiments (DOE) table framed in accordance with L9 orthogonal array considering Taguchi Design model from Minitab Software. The process parameters considered in present work involved design specific parameters like tool rotational speed (800, 1000, and 1200 rpm),
traverse feed (80, 100, and 120 mm/min) and tool pin configuration (cylindrical, cylindrical taper, and triangular). The weld joint of trial 1 is as shown in figure 2. The details of welding parameters and its levels are given in Table 3. During the process of welding, Aluminium AA 7075 is located on retreating side while Aluminium AA 5052 is located on advancing side. The tool shoulder is plunged into the plates fastened on the special fixtures clamped on the table of the machine and the FSW process carried out in accordance with the Design of Experiments. The process parameters are optimized by considering the forces and torque encountered during the process.

3. Results and Discussions
The experimental trials are carried out in accordance with the “L9 Taguchi Orthogonal Array (OA)”, which is given in the Table 4. The outcomes of the experimental trials are validated from the optimum process parameters identified from the graphs.

The “Orthogonal Array (OA)” is a scientifically disciplined frame work model, used for evaluating and optimizing the process parameters. During welding process, there are essentially two forces viz., Normal Force, Traverse Force, and Spindle Torque. The optimization of these forces are important for evolving a sustainable methodology.

3.1. S1F1T1 Condition
3.1.1. Normal Load for S1F1T1 Condition. The normal load exerted by the tool on the work piece during the course of welding for spindle speed (S1) of 800 rpm, Feed (F1) of 100 mm/min
Figure 2. Friction Stir Weld Joint of AA 7075 and AA 5052

Figure 3. The display of variation of loads and torque during welding from FSW machine

Table 4. DOE– L9 Orthogonal Array

| Exp. No. | Designation of the Conditions | Rotational Speed (RPM) | Feed (mm/min) | Tool Offset (mm) | Tool Pin Profile |
|----------|--------------------------------|------------------------|---------------|-----------------|-----------------|
| 1        | S1F1T1C                        | 800                    | 100           | (-)0.5          | Cyl.            |
| 2        | S1F1T1CT                       | 800                    | 100           | (-)0.5          | Cyl.(Tp)        |
| 3        | S1F1T1T                        | 800                    | 100           | (-)0.5          | Tr.             |
| 4        | S2F2T2C                        | 1000                   | 120           | 0               | Cyl.            |
| 5        | S2F2T2CT                       | 1000                   | 120           | 0               | Cyl. (Tp.)      |
| 6        | S2F2T2T                        | 1000                   | 120           | 0               | Tr.             |
| 7        | S3F3T3C                        | 1200                   | 140           | 0.5             | Cyl.            |
| 8        | S3F3T3CT                       | 1200                   | 140           | 0.5             | Cyl.(Tp.)       |
| 9        | S3F3T3T                        | 1200                   | 140           | 0.5             | Tr.             |
and tool offset of (-) 0.5 mm for cylindrical pin profile (C), cylindrical taper (CT) pin profile and Triangular (T) pin profile is given in figure 4, it is herewith noted that the normal load exerted by the tool on workpiece with time is maximum for cylindrical tool profile and the time duration of the normal load acting on the workpiece is also found to be maximum for cylindrical tool pin profile, followed by cylindrical taper and triangular tool profile, this is because, the cylindrical pin profile offered resistance to the flow ability of the workpiece around the tool all along the length of the weld zone. The peak normal load is for S1F1T1C condition, at a magnitude of 15 kN, followed by S1F1T1CT and S1F1T1T conditions. The time period for normal loads acting on the workpiece during the course of friction stir welding is 140 seconds for S1F1T1C condition, 90 seconds for S1F1T1CT condition, and 70 seconds for S1F1T1T condition.

![Figure 4. Normal Load for S1F1T1 conditions](image)

3.1.2. Transverse Load for S1F1T1 Condition. The traverse load exerted by the tool on the workpiece during the course of welding for spindle speed (S1) of 800 rpm, Feed (F1) of 100 mm/min and tool offset of (-) 0.5 mm for cylindrical pin profile (C), cylindrical taper (CT) pin profile and Triangular (T) pin profile is given in Figure 5, it is herewith noted that the traverse load exerted by the tool on workpiece with time is maximum for cylindrical tool profile and the time duration of the traverse load acting on the workpiece is also found to be maximum for cylindrical tool pin profile, followed by cylindrical taper and triangular tool profile. The peak traverse load is for S1F1T1C condition, at a magnitude of 1.75 kN, followed by S1F1T1CT and S1F1T1T conditions. The time period for traverse loads acting on the workpiece during the course of friction stir welding is 140 seconds for S1F1T1C condition, 90 seconds for S1F1T1CT condition, and 70 seconds for S1F1T1T condition.

3.1.3. Spindle Torque for S1F1T1 Condition. The spindle torque of the tool on the workpiece during the course of welding for spindle speed (S1) of 800 rpm, Feed (F1) of 100 mm/min and tool offset of (-)0.5 mm for Cylindrical pin profile (C), Cylindrical taper (CT) pin profile and
Triangular (T) pin profile is given in figure 6, it is herewith noted that the spindle torque of the tool on workpiece with time is maximum for cylindrical tool profile and the time duration of the torque acting on the workpiece is also found to be maximum for cylindrical tool pin profile, followed by cylindrical taper and triangular tool profile. The peak spindle torque is for S1F1T1CT condition, at a magnitude of 14 N·m, followed by S1F1T1C and S1F1T1T conditions. The time period for traverse loads acting on the workpiece during the course of friction stir welding is 140 seconds for S1F1T1C condition, 90 seconds for S1F1T1CT condition, and 70 seconds for S1F1T1T condition.

![Figure 5. Traverse Load for S1F1T1 conditions](image)

3.2. S2F2T2 Condition

3.2.1. Normal Load for S2F2T2 Condition. The normal load exerted by the tool on the workpiece during the course of welding for spindle speed (S2) of 1000 rpm, Feed (F2) of 120 mm/min and tool offset (T2) of 0 mm for cylindrical pin profile (C), cylindrical taper (CT) pin profile and Triangular (T) pin profile is given in Figure 7, it is herewith noted that the normal load exerted by the tool on workpiece with time is maximum for cylindrical taper and triangular tool profile. The peak normal load is for S2F2T2CT condition, at a magnitude of S2F2T2C and S2F2T2T conditions. The time period for normal loads acting on the workpiece during the course of friction stir welding is 138 seconds for S2F2T2C condition, 91 seconds for S2F2T2CT condition, and 72 seconds for S2F2T2T condition.

3.2.2. Transverse Load for S2F2T2 Condition. The traverse load exerted by the tool on the workpiece during the course of welding for spindle speed (S2) of 1000 rpm, Feed (F2) of 120 mm/min and tool offset of 0 mm for cylindrical pin profile (C), cylindrical taper (CT) pin profile and Triangular (T) pin profile is given in Figure 8, it is herewith noted that the traverse load exerted by the tool on workpiece with time is maximum for cylindrical tool profile and the time duration of the traverse load acting on the workpiece is also found to be maximum for cylindrical
tool pin profile, followed by cylindrical taper and triangular tool profile. The peak traverse load is for S2F2T2C condition, at a magnitude of 2.25 kN, followed by S2F2T2CT and S2F2T2T conditions. The time period for traverse loads acting on the workpiece during the course of friction stir welding is 138 seconds for S2F2T2C condition, 91 seconds for S2F2T2CT condition, and 72 seconds for S2F2T2T condition.

3.2.3. Spindle Torque for S2F2T2 Condition. The spindle torque of the tool on the workpiece during the course of welding for spindle speed (S2) of 1000 rpm, Feed (F2) of 120 mm/min and tool offset of 0 mm for Cylindrical pin profile (C), Cylindrical taper (CT) pin profile and
Triangular (T) pin profile is given in Figure 9, it is herewith noted that the spindle torque of the tool on workpiece with time is maximum for cylindrical tool profile and the time duration of the torque acting on the workpiece is also found to be maximum for cylindrical tool pin profile, followed by cylindrical taper and triangular tool profile. The peak spindle torque is for S2F2T2CT condition, at a magnitude of 6.2 N-m, followed by S2F2T2C and S2F2T2T conditions. The time period for traverse loads acting on the workpiece during the course of friction stir welding is 138 seconds for S2F2T2C condition, 91 seconds for S2F2T2CT condition, and 72 seconds for S2F2T2T condition.

![Figure 8. Traverse load for S2F2T2 conditions](image1)

![Figure 9. Spindle Torque for S2F2T2 conditions](image2)

3.3. S3F3T3 Condition

3.3.1. Normal Load for S3F3T3 Condition. The normal load exerted by the tool on the workpiece during the course of welding for spindle speed (S3) of 1200 rpm, Feed (F3) of 140 mm/min and tool offset of 0.5 mm for cylindrical pin profile (C), cylindrical taper (CT) pin profile and Triangular (T)
pin profile is given in Figure 10, it is herewith noted that the normal load exerted by the tool on workpiece with time is maximum for cylindrical tool profile and the time duration of the normal load acting on the workpiece is also found to be maximum for cylindrical tool pin profile, followed by cylindrical taper and triangular tool profile, this is because of the fact that the cylindrical tool profile offers more resistance to the flow of the work piece material during the due course of friction stir welding process. The peak normal load is for S3F3T3C condition, at a magnitude of 18 k N, followed by S3F3T3CT and S3F3T3T conditions. The time period for normal loads acting on the workpiece during the course of friction stir welding is 136 seconds for S3F3T3C condition, 87 seconds for S3F3T3CT condition, and 69 seconds for S3F3T3T condition.

3.3.2. Transverse Load for S3F3T3 Condition. The traverse load exerted by the tool on the workpiece during the course of welding for spindle speed (S3) of 1200 rpm, Feed (F3) of 140 mm/min and tool offset of 0 mm for cylindrical pin profile (C), cylindrical taper (CT) pin profile and Triangular (T) pin profile is given in Figure 11, it is herewith noted that the traverse load exerted by the tool on workpiece with time is maximum for cylindrical tool profile and the time duration of the traverse load acting on the workpiece is also found to be maximum for cylindrical tool pin profile, followed by cylindrical taper and triangular tool profile. The peak traverse load is for S3F3T3CT condition, at a magnitude of 1.45 k N, followed by S3F3T3C and S3F3T3T conditions. The time period for traverse loads acting on the workpiece during the course of friction stir welding is 136 seconds for S3F3T3C condition, 87 seconds for S3F3T3CT condition, and 69 seconds for S3F3T3T condition.

![Figure 10. Normal load for S3F3T3 conditions](image)

3.3.3. Spindle Torque for S3F3T3 Condition. The spindle torque of the tool on the workpiece during the course of welding for spindle speed (S3) of 1200 rpm, Feed (F3) of 140 mm/min and tool offset of 0.5 mm for Cylindrical pin profile (C), Cylindrical taper (CT) pin profile and Triangular (T) pin profile is given in Figure 12, it is herewith noted that the spindle torque of the tool on workpiece with time is maximum for cylindrical tool profile and the time duration of the torque acting on the workpiece is also found to be maximum for cylindrical tool pin profile, followed by cylindrical taper and S3F3T3C and S3F3T3T conditions. The time period for traverse loads acting on the workpiece during the course of friction stir welding is 136 seconds for S3F3T3C condition, 87 seconds for S3F3T3CT condition, and 69 seconds for S3F3T3T condition.
3.4. Summary of force and torque optimizations
The comprehensive review of the normal load, traverse load and torque versus time for different process conditions has provided valid base for deciding the optimum process parameters for Friction Stir Welding (FSW), the dissimilar aluminium alloys with minimum time duration and optimized forces; The Table 5 gives the time duration and the subsequent peak normal loads, peak traverse loads and spindle torque for friction stir welding at different conditions tabulated from the careful observations of the graphs, it is herewith observed that the time duration of welding and the forces acting on the tool pin profile during the process are optimized when a triangular pin profile is used for friction stir welding the plates at a spindle speed of 1200 rpm and feed rate of 140 mm/min with a positive tool offset of 0.5 mm.

William R L et al., have reported the variation of force and torque during the friction stir welding, they have investigated the relationship between axial force and torque and have plotted the variation of forces and torque with time. The results from the present work follows the same trend of peak force and torque variations and likewise when, the torque increases, so does the
Maurizio B, et al., have extensively worked on the sustainability of friction stir welding of aluminium sheets, and have identified that the environmental impact of friction stir welding in terms of the dwell time and peak forces and torque encountered during the process, the findings of their work have been in parallel with the findings of the present work, with respect to the reduction of the period for friction stir welding of dissimilar aluminium alloy plates using triangular pin profile, viz., 69 seconds for the completion of the process of friction stir welding for 170 mm length among all the experimental trials design according to taguchi’s L9 orthogonal array (OA) [9].

3.5. Microstructure

The microstructure of the top and transverse section of the friction stir weld zone is studied using the SEM images captured using a VEGA3 TESCAN machine.

3.5.1. Microstructure of the top surface. The morphology of the top surface of the L9 weld joints processed at 1200 rpm rotational speed, feed rate of 100 mm/min, with a tool offset of -0.5 mm for tapered cylindrical pin profile are studied using the SEM images captured using VEGA TESCAN scanning electron microscopes at various magnifications and the microstructure observed at 1.5 kx is given in the Figure 13(a). It is evident from the microstructure of the weld zone that the bonding has occurred coherently between the different zones, which eventually results in the formation of striated bands of the weldment.

3.5.2. Microstructure of the transverse surface. The morphology of the transverse surface of the L9 weld joints processed at 1200 rpm rotational speed, feed rate of 100 mm/min, with a tool offset of -0.5 mm for tapered cylindrical pin profile are studied using the SEM images captured using VEGA TESCAN scanning electron microscopes various magnifications and the microstructure observed at 1.5 kx is given in the Figure 13(b). It is evident from the microstructure of the transverse weld zone that the interstitial transverse bonding has occurred coherently between the different zones in the transverse section, resulting in the formation of striated transverse bands of the weldment in friction stir welded joints.

Further, Dhananjayalu avula, et. al., have carried out extensive work on the microstructure of the friction stir weld zone, they have critically observed that the nugget zone exhibits very fine grains, also the atomic grains depict an equi axed elongated grain structure all along the periphery of the thermo mechanically affected zone. The same observations are found in the microstructure of the friction stir weld dissimilar alloy joints observed in the present work [1].

Table 5. Peak Loads and Duration for FSW at different conditions

| Exp. No. | Designation of the Conditions | Duration For FSW (S) | Peak FN k N | Peak FT k N | Peak ST N-m |
|----------|-------------------------------|----------------------|-------------|-------------|-------------|
| 1        | S1F1T1C                       | 140                  | 15          | 1.75        | 12          |
| 2        | S1F1T1CT                      | 90                   | 13.5        | 1.35        | 14          |
| 3        | S1F1T1T                       | 70                   | 13          | 1.5         | 13          |
| 4        | S2F2T2C                       | 138                  | 17          | 2.25        | 6.1         |
| 5        | S2F2T2CT                      | 91                   | 17.5        | 2.2         | 6.2         |
| 6        | S2F2T2T                       | 72                   | 15          | 2.1         | 6           |
| 7        | S3F3T3C                       | 136                  | 18          | 1.4         | 9.6         |
| 8        | S3F3T3CT                      | 87                   | 15          | 1.45        | 10.2        |
| 9        | S3F3T3T                       | 69                   | 12.5        | 1.25        | 8.8         |
4. Conclusions
The critical analysis of the outcomes of the experimental design has yielded several conclusions which are comprehensively put forth in the current section.

From, the analysis of traverse load, normal load, and spindle torque; the optimized set of process parameters of 1200 rpm tool rotational speed, 140 mm/min feed rate, tool offset of 0.5 mm and triangular pin profile, will give an effective weld of AA 7075 and AA 5052 alloy. Further, the SEM images confirm and acknowledge the formation of strong bonds between the atoms across the subsurface in the weldments. It gives an overview of the fracture type, weld zone atomic morphology, and the passivation of the corrosion samples over a period of time. The SEM images of the weld joint clearly exhibits the intrinsic strong bonding between the atoms in the interstitial zones of the weldment, further, the micro coring and segregation of the atoms leads to better solutionizing. The optimized process parameters lead to sustainable friction stir welding of dissimilar aluminium alloy joints with reduced time duration of 69 seconds for friction stir welding the 170 mm length aluminium alloy joints with optimized peak forces and torque.

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