Effects Of Welding On The Fatigue Behaviour Of Commercial Aluminum AA-1100 Joints

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Abstract: Friction Stir Welding (FSW) is an budding solid state welding process, which is frequently used for joining aluminum alloys where materials can be joined without melt and recast. Therefore, when welding alloys through FSW the phase transformations occurs will be in the solid state form. The present work is aimed in evaluating the fatigue life of friction stir welded commercial grade aluminum alloy joints. The commercial grade AA1100 aluminum alloy of 12mm thickness plate is welded and the specimens are tested using a rotary beam fatigue testing machine at different stress levels. The stress versus number of cycles (S-N) curves was plotted using the data points. The Fatigue life of tungsten inert gas (TIG) and metal inert gas (MIG) welded joints was compared. The fatigue life of the weld joints was interrelated with the tensile properties, microstructure and micro hardness properties. The effects of the notches and welding processes are evaluated and reported.

Keywords : Friction Stir Welding, TIG Welding, MIG Welding, AA 1100 Aluminum Alloy, Fatigue life, Tensile Strength, Micro hardness, Micro structure

1. INTRODUCTION
According to Balasubramanian et al [1], fatigue crack growth parameters of Electron Beam Welding (EBM), Gas Tungsten Arc Welding (GTAW), and Laser Beam Welding (LBM) joints of Ti-6Al-4V were evaluated. Compared to EBW and GTAW, LBW has higher crack growth resistance. This is because of the occurrence of fine lamellar shaped ‘α’ microstructure in the welded material formed due to faster cooling with less heat input. Arivazhagan et al. study explains the Shielded Metallic Arc Welding of 304B Stainless Steel. The investigation mainly focused on studying significance of heat on the heat affected zone cracking. The increase in the heat affected zone (HAZ) was noted while increasing the heat input. The possible reasons for resistance to liquation cracking is due to increase in eutectic boride phase content with increase in heat input hence the possibility of crack healing during welding and low level of joint resistance and also less sulphur and phosphorus contents [2]. TC4 titanium alloy welded by Double sided Gas tungsten arc welding process was examined by Gao Hong Ming et al. Variation in the microstructure and mechanical properties of welded TC4 titanium alloy when welded by GTAW process and conventional GTAW process was detailed. The result proved the better performance of double sided GTAW process through the improvement in the welding efficiency reduced welding deformation [3]. Friction welding was done on pure aluminum to C1100 tough pitch copper and investigated for tensile Strength and fatigue strength by Yoshiaki Yamamoto et al. Joints with stable tensile property have higher fatigue strength than the joints which has low tensile strength [5]. Biswas et al by welding the commercial grade aluminium
alloys using friction stir welding process studied the influence of the tool pin geometry, effect of tool rotation and welding speeds on the mechanical properties of the joints made [6]. Sefika Kasman detailed the effect of tools type, rotation speed of tool and welding speed of friction stir welding process on tensile strength of welded AA6082 and AA7075 samples [7]. By welding 3003-O Aluminum Alloys through Friction Stir Welding process Hakan Aydin et al examined the significance of welding parameters on the fatigue behavior. In that research fully reversed uniaxial fatigue tests have been performed in order to investigate the fatigue behaviors of single-sided friction stir butt welds in different welding conditions and concluded that all FS welds in different welding conditions exhibit lower fatigue life than the base metal [8]. Influence of welding parameters of friction stir welding process on the mechanical behavior was studied by Richa Sahni et al. Tensile strength decreases significantly with increase in tool rotation speed (rpm) and pin diameter. Impact strength decreased with an increase in speed of the tool rotation (rpm) and pin diameter and increases with increase in welding speed [9]. Cavaliere et al analyzed the effects of rotating and welding speed on the mechanical and microstructural properties. Different welding trails with variable rotating speed of the tool and different velocity. Three different rotational speeds were used with three different welding velocities. This concludes that the tensile strength is high correspondence to the high rotational speed and low welding velocity. The fatigue endurance was better in this research for moderate speed [11]. Friction surfaced Aluminium alloy 5052 was investigated by Hidekazu Sakihama and the influence of the surfacing conditions was studied [12]. Aidy Ali et al investigated the Fatigue damage of 2024-T351 Aluminum alloy friction stir welded joints the comprehensive characterizations of micro and macro mechanics of FSW 2024-T351 were performed based on the macrostructure, microstructure, hardness, residual stress and cyclic deformation behavior[13]. Through the combined effect of fusion and solid state welding process Al 6061 alloy and AISI 1018 steel was welded and investigated by Chen et al. Inter-metallic compounds Al13Fe4, Al5Fe2 are found to exist in the nugget zone. The study states acoustic emission technique as more preferable method for monitoring the quality of welding process and the detection of tool breakage [14]. However none of the work was reported on the fatigue behavior of AA-1100 weld joints.

2. EXPERIMENTAL PROCEDURE
2.1. Base metal properties
In this work AA-1100 Commercial Grade Aluminum Alloy plate of 12mm thickness of 150 x 150 mm was welded by three welding processes, such as Friction Stir welding (FSW), Tungsten Inert Gas welding (TIG) and Metal Inert Welding (MIG). The mechanical properties of the Al-AA-1100 properties are shown in table 1.

| BASE METAL | Yield Strength (MPa) | Tensile Strength (MPa) | Elongation (%) | Hardness (Hv 5) |
|------------|----------------------|------------------------|----------------|----------------|
| AA 1100    | 105                  | 110                    | 12             | 60             |

Vickers’s Micro-hardness testing machine is used for the testing of the base metal with .5 kg load. The microstructure of the joint was analyzed at the various locations using Optical microscope (MAKE: MEIJI, JAPAN; MODAL: MIL7100). The microstructure of the weld joints was observed using optical Microscopic image. The specimens were mechanical polished with emery sheets and the Keller’s reagent was applied for 5 seconds.

2.2. Filler metal properties
Alloy AA-4043 contains 5% silicon which is suitable to weld similar and dissimilar cast and wrought aluminum parts. Alloy AA 4043 is used mainly for the purpose of minimizing the cracks which are the most common problems in Aluminum welding and also increasing the fatigue life of the material. The mechanical behavior of the filler metal is shown in table 2.
Table 2. Mechanical Properties of Filler Metal

| FILLER METAL | Tensile Strength (MPa) | Yield Strength (MPa) | Elongation % |
|--------------|------------------------|----------------------|--------------|
| AA 4043      | 120                    | 40                   | 8            |

2.3. Preparation of tool
The present investigation used a non consumable high speed steel tool of welding the joints. With this tool it is possible to produce friction heating at weld joints and also to generate plastic deformation of work piece material in a solid phase, which produces in complex mixing.

Table 3. Dimensions of the Tool

| Tool                | Tool profile            | Probe diameter       | Pin length | Shoulder Diameter |
|---------------------|-------------------------|----------------------|------------|-------------------|
| Super High Speed Steel | Cylindrical and Threaded | 11mm through 9mm     | 11mm       | 30mm              |

Figure 1. FSW Tool
The 30mm diameter cylindrical rod is shaped into a single-piece monolithic design whose tool profile consists of the probe and a shoulder. The different dimensions of the tool are shown in table 3 and the typical tool is presented in figure 1.

2.4. Fabrication of joints
Base metal was sliced into 150 x 75 x 12mm from the original 150 x 150 x 12 mm plates. Square Butt joint configuration has been prepared for FSW joint. Edge preparations for the TIG and MIG joints are carried to attain single V-Groove Butt joints with 60° included angle. The root gap for TIG was 2 mm and for MIG was 1.5 mm was maintained.

The rolled plate of 12mm thick Al-1100 alloy is used to fabricate the joints as the base metal (BM). Single V butt joint configuration was prepared to fabricate the joints using GTAW and GMAW processes. Using FSW process square butt joints was made in the preferred metal. Table 4 presents the weld processing conditions used to weld the joints.
Table 4. Parameters of welding

| Process | Parameters                          |
|---------|------------------------------------|
| FSW     | Tool speed - 400 rpm               |
|         | Welding Speed - 20mm/s             |
| TIG     | Current – 220 A                    |
|         | Voltage – 21 V                     |
| MIG     | Current – 160 A                    |
|         | Voltage – 21 V                     |

3. SPECIMEN PREPARATION
The sample was prepared to estimate the result of tensile properties as per ASTM. Further, the smooth (un-notched) tensile samples were prepared to appraise the transverse tensile properties of the joint such as yield strength, tensile Strength and elongation. However, the notched specimens were equipped to assess notch tensile strength and notch strength ratio of the joints. The microstructure of the joint was analyzed at the various locations using optical microscope the microstructure investigation of the joints of Optical Microscope observation was done with the aid of Keller’s Reagent. Vickers’s micro-hardness testing machine was employed with 0.5kg load for measuring the hardness across the weld as per ASTM guidelines. Thirty reading were taken in close proximity distance (with .5mm in weld bead and 1mm in HAZ and BM) in each zone with .5kg load and a dwell time of 15 seconds and the mean values are used for further analysis and discussions. The Stress-Strain curve is constructed from the load-elongation measurements.

The fatigue assessment involves comparisons of the action of the component or the structure under consideration will be required to sustain its design strength with its resistance to fatigue. To evaluate the fatigue (S-N) Behavior, the weld joints were sliced using DOALL machine as shown in figure 2. According to ASTM, two specimens were subjected to load to find the fatigue strength.

![Figure 2. DOALL Cutter Machine](image)

4. RESULT AND DISCUSSION
4.1 Tensile properties
As per ASTM, two specimens were fabricated and tested to determine the transverse tensile properties in accordance with mechanical testing of welds. The un-notched tensile specimens were prepared to examine the tensile properties and Joint efficiency. Notch Tensile strength and Notch Strength Ratio of the joints were found on the prepared notched specimens. Tensile test is carried out in 100kN, Universal Testing Machine (MAKE: FIE-Bluestar, India; MODAL: UNITEK 94100). The tensile results are shown in figure 3(a).

The results show that Yield strength of FSW is 77.8MPa which is 91.30 % of Base Metal, and also the Yield Strength of MIG and TIG are 76.38MPa, 74.86MPa which are 90.7 % and 88.9% of that of the Base Metal. Graph in figure 3(b) shows the comparison of the Yield strength for different processes weld joints. It is found that the FSW welding process has yield strength 1.3 % higher to that of MIG and 2.4 % to that of TIG process. In this process the FSW process has high yield strength. This is due to the larger grain structure which increases the yield point in the process and takes longer time to fail.
It is also found that the tensile strength of the FSW is 89.27 MPa which is 79.6% of that of Base Metal which has 112.2 Mpa. The comparison of the Tensile strength of the different processes weld joints are shown in the form of graph in figure 3(c). The other processes such as TIG and MIG are 76.86% (86.24 MPa) and 78.1% (87.64 MPa) of that of BM. Here the FSW process has high tensile strength which is 2.7% and 1.46% higher than the TIG and MIG processes. Thus, higher the tensile strength the stronger the material will help in the longer use of the material and improves the fatigue strength.

The initial specimen size was 100 mm; since we use tensile test the result specimen will be elongated more than the initial size. It is seen that the % elongation of the welds of different processes is different for each one. The comparison of the percentage of elongation of the different processes weld joints are shown in the form of graph in figure 3(d). The FSW process has elongated more comparing other process such as TIG and MIG. It has elongated 15.4% which is 87.79% of elongation of the BM while the other processes only elongated 13.3% (TIG) and 12.3% (MIG) which are 75.82% and 70.12% of that of the BM respectively. The FSW process elongates more and it takes more time to break which not only increases the Tensile strength but also affects the life of the metal.

The initial diameter of the tensile specimen is 8 mm. After the test due to load its area is reduced. The comparison of the Reduction of Area of the different processes weld joints are shown in the form of graph in figure 3(e). The BM has elongated to about 73.25 % from the initial area. The welds have reduced to about 65.5% (MIG), 70.26% (TIG), and 71.25 % (FSW) of that of the original area. It FSW process reduced about 97.25% of the BM while others reduced to 89% (MIG) and 94.2%. The FSW process has 1% higher than TIG and 5.75% MIG process. It shows that the weld joint has high ductile property which in turns increases the strength.

The Notch strength can be got by creating a notch to induce the breakage of the metal. This Strength shows us the real tension of the metal, the total load tension acts on the notch which induce the breaking, which tests the weld area. The comparison of the Notch strength of the different processes weld joints are shown in the form of graph in figure 3(f). It shows that the BM has strength of 157.36 MPa. The Notch Strength of the weld processes are 142.74 MPa (FSW), 130.31 MPa (TIG), and 113.9 MPa (MIG). The FSW process has high Notch Strength which is 90.70% of that of the BM. The other processes have 82.81% (TIG) and 72.38% (MIG) of that of the BM. The FSW process is 7.81% higher than the TIG and 18.32% higher than MIG processes respectively. The FSW process has the high strength comparatively and the life of metal welded by the FSW process is high.

The Notch Strength Ratio (NSR) is the correlation of tensile and notch strength which shows the property of the metal. The brittleness of the metal can be found out by the NSR. The NSR of the BM is 1.54 and the weld process FSW, TIG, and MIG have 1.59, 1.52, 1.32 respectively. Clearly we see the metal is a ductile material. The comparison of the Notch Strength Ratio of the different processes weld joints are shown in the form of graph in figure 3(g). The NSR of weld processes are 98.7% (TIG) and 85.71% (MIG) of that of the BM while FSW process is 103.24% of that of the BM which tells the ductility increases with welding with FSW process. Also the FSW process weld has NSR 4.54% (TIG) and 17.53% (MIG) higher than the corresponding processes. This ensures the metal is ductile which increases the strength and life of the metal that can be got by Welding in FSW process which increases the ductility of the BM.

The joint efficiency is the ratio of strength of welds with base metal or simply the strength of the weld. It shows that the FSW process has 87.77% joint efficiency while the MIG and TIG have 83.88% and 84.17%. The joint efficiency is given in graphical form in figure 3(h). This tells us that the weld of the FSW is 3.89% higher than MIG and 3.6% higher than TIG process. Thus we can conclude the FSW process has the strongest welds comparatively.

All the variable of tensile test shows us that the Friction Stir Welding (FSW) process is the most suitable welding process for joining AA-1100 Al Alloy. It tensile properties are higher to that of TIG and MIG processes.
4.2. Micro hardness

Vickers's micro-hardness testing machine (MAKE: SHIMADZU, JAPAN; MODAL: HMV-2T) was employed with .5kg load for measuring the hardness across the weld. Thirty reading were taken in close proximity distance (with .5mm in weld bead and 1mm in HAZ and BM) in each zone with a load of .5kg with the dwell time of 15 seconds and the mean values are used for further analysis and discussions.
The Micro-Hardness distribution of the weld joints in the weld bead is given in figure 4. The different welding processes FSW, TIG, MIG weld joints are calculated for their Micro-hardness and line graph is drawn. The Micro-hardness in the weld bead of different process are different due to the different conditions.

The TIG process has the high hardness in weld bead following by the MIG process. The FSW process has low Micro-Hardness which is in agreement with the hardness of the Base Metal (BM). The hardness difference is due addition of the filler metal of 4043. The Base Metal has a hardness average of 37 Hv; the FSW process has 36 Hv due to its equi-axial grain structure in the stirred zone. The stirred zone has a very good structure and the heat produced is less comparing the other processes. The high heat and addition of filler material raises the hardness of the TIG and MIG process weld joints. In the weld bead TIG has 57Hv while MIG has 48Hv hardness. However FSW joints remain higher than the other processes to the closeness of the BM hardness.

In the figure 5 the hardness distribution of the weld joints across the base metal, Heat Affected Zone, and the Weld Bead are shown. The TIG joints are close to the BM in the un-welded region and it increases in the HAZ and it is maximum at the weld bead. This is due to the increase in heat and the change of the grain structure while welding. Similarly the MIG joints have high hardness in weld bead and HAZ as it comes back to nominal value after the HAZ back to the BM across the weld line.

But the FSW process is uniform across the weld line where its heat is only 80% of the base metal in the Stirred Zone. The heat distribution is uniform and the zones are well distributed to maintain the hardness. Almost a symmetric hardness distribution occurred across the weld region. A comparable hardness fashion
was noted between the BM and HAZ and also it was observed that the average of hardness of the BM and HAZ were just about 36 Hv and 35 Hv, respectively. As the outcome of this study, there is no high degree disparity in hardness between the BM and HAZ at both sides of the weld. The FSW joints have the hardness of the BM and are to have long life with high strength.

The different Micrographs of the welded joints of the different processes are shown in the figure 6 (a-d). The MIG joint is figure 6(a) which shows the grain structure of the weld bead. The grain structure was found to be loose and there were defects like blow holes which may be caused by the impurities and moisture in shielding. This was found to be cluster porosity which was caused due to the changing welding conditions. The TIG joint in figure 6(b) shows the micro-structure of the weld bead. The grain structure is continuous but the grain size was not equal and there was uneven ripples and has inconsistent solidification pattern which is the result of inconsistent in heat input. There are also small porosity defects in the line connecting the BM and WB (Weld Bead). The HAZ is found to have the grain structure a bit loose compared to the BM.

The FSW joint in figure 6(c) shows the microstructure of the stirred zone. Four different micro structural zones were shown in the weld zone of all FSW trials. These zones
1) heat-affected zone (HAZ);
2) unaffected base metal (BM);
3) weld nugget zone (WNZ); and
4) thermo mechanically affected zone (TMAZ)

HAZs were observed on both sides, and there were different boundaries between the other zones. While the HAZs consisted of the coarsened grains compared with the BM due to rising the weld temperature, the TMAZs shows the deformed and elongated structure in the region of WNZs since, deficient plastic deformation with increased welding temperature. The WNZs were examined by fine and equiaxed - recrystallized grains due to intense plastic deformation and thermal exposure during the FSW process. The figure 6(d) shows the Base Metal microstructure grain. The small pores seen are due to the etching of the metal before the Optical Microscopic investigation. The line joining the different grains is clearly visible in the microstructure graph.

The different micrographs show that the MIG has defects (blow holes, porosities) which affect the strength and life of the metal. The TIG has a moderate structure but the life is reduced due the uneven distribution of the heat input during the welding. Also considering the micro-hardness the TIG and MIG joint have high hardness from the base metal, these accords for the lesser strength and reduces the life of the metal.

However the FSW process has the best structure compared to other welding processes. The equiaxed structure in stirred zone results in better properties of strength and the life of the material is increased due to the good joint efficiency. All the parameters come to the point which implies the Friction Stir Welding process is the best process welding AA-1100 Al alloy joints. Also its corrosive strength is good due to the good joint welding and structure implies no defects in the Microstructure.
4.3. Fatigue (S-N) Behavior

These samples are tested at various stress level and the values were noted. An average of the stress values is considered here to plot S-N curves of un-notched specimens. The S-N curve for high cyclic load fatigue nature is described as

\[ S^0 N = A \]

Where ‘S’ is the stress amplitude, ‘n’ is a constant (slope of the curve), ‘N’ is the number of cycles of failure and ‘A’ is a constant (intercepts of curve). While comparing the fatigue strengths loaded at same condition of different welded joints, it is easy to denote the values of the fatigue strength in terms of $10^5$, $10^6$, $10^7$ cycles. Traditionally $2 \times 10^6$ cycles has been used. The cause of the fatigue strength is calculated by comparing the S-N curves obtained for both notched, un-notched specimens.

| S.No. | Type of joint | Fatigue strength (unnotched specimen) @ $1 \times 10^6$ cycles (MPa) | Fatigue strength (notched specimen) @ $1 \times 10^6$ cycles (MPa) |
|-------|---------------|-------------------------------------------------|-------------------------------------------------|
| 1.    | Parent Metal  | 45                                              | 27                                              |
| 2.    | FSW Joint     | 40                                              | 24                                              |
| 3.    | TIG Joint     | 35                                              | 22                                              |
| 4.    | MIG Joint     | 30                                              | 18                                              |

The table 5 shows the fatigue strengths of the parent metal and the joints of the notched and un-notched joints. It is clearly seen the different processes have different effects on the Fatigue life of the metal. The notched specimens have values with distinct difference because we induced the failure by creating a notch.
The un-notched or smooth specimens show the real properties of the metal. It takes a little longer to fail since there is no notch present. The un-notched and notched specimens of different welding processes are shown in the S-N curve in figure 7(a&b). This shows us that the base metal has the most number of cycles or the higher life compared to the other welded joints. The life of the metal depends on various factors varying welding parameters, different welding processes etc. In this research the smooth specimens of the welded joints show different wavelength. The next to the BM is the FS welds followed by the TIG welds and MIG welds.

The FSW process has high fatigue life mainly because of these reasons: The grain structure is most important which normally has over about 1,000,000 grains which are closely packed after the welding process due to the shoulder. Then there is the residual compressive force which stops the crack growth due to the axial force given during the welding process. Also there is the boundary structure, the grain boundaries of the FS weld joints are very close and they are very hard to break in order to fail the metal. The tensile strength supports the fatigue result. The Micro-hardness and Microstructure of the joints show that FSW process clearly has the advantage over the other processes.

The other process TIG is next to FSW weld joints. They have moderate grain structure and moderate strength. Defects reduce the fatigue life and strength of the material. The grain structure of the TIG weld is loose compared to the FS welds hence it is easy to break. The tensile strength also showed that the FSW process had the higher strength. The Micro-hardness of TIG welds was higher in value but the FSW welds had the higher Hardness relative to the Base metal.

The MIG process had many defects such as a cluster of porosities. The Microstructure also showed that there were porosities found in weld bead. It reduces the strength and lowers the life of the metal. The Micro-hardness had the lower value compared to FSW process relatively close to the Base Metal. Every parameter and tests shows us the Friction Stir Welded joints had the high number of cycles which implies longer life and high fatigue strength.

5. CONCLUSIONS
The analyses performed on the microstructure, micro-hardness, tensile properties, fatigue behavior in the Al-AA-1100 alloy demonstrate relationships between material properties and the response of welds. Comparison of microstructure analysis, micro-hardness profiles for the three welding processes confirms that tensile properties are governed primarily by the micro-hardness profile but may be influenced by micro structural features such as secondary phase distributions.

- The comparison of tensile test of the different welding processes shows that the Friction Stir Welded joints have higher properties than the MIG and TIG joints. The following justifies the above statement.
- The FS welds have Yield strength 91.30 % of Base Metal, while the MIG and TIG have 90.7 % and 88.9% of that of the Base Metal respectively. It is found that the FSW welding process has yield strength 1.3 % higher to that of MIG and 2.4 % to that of TIG process. The FSW process has high yield strength.
The FSW process has tensile strength which is 2.7% and 1.46% higher than the TIG and MIG processes. The tensile strength of the FSW is 79.6% of that of Base Metal while the TIG has 76.8% and MIG has 78.1%.

The elongation of FS weld joints is 87.79% of elongation of the BM while the other processes only elongated TIG weld joints 75.82% and MIG weld joints were 70.12% of that of the BM respectively.

It FSW process reduced about 97.25% of the BM while others reduced to 89% (MIG) and 94.2% (TIG) weld joints. The FSW process is 2.5% higher than TIG process and 8.25% than MIG process.

The FSW process has Notch Strength which is 90.70% of that of BM. The other processes have 82.81% (TIG) and 72.38% (MIG) of that of the BM. The FSW process is 7.81% and 18.32% higher than the TIG and MIG processes respectively.

The NSR of weld processes are 98.7% (TIG) and 85.71% (MIG) of that of the BM while FSW process is 103.24% of that of the BM which tells the ductility increases with welding with FSW process. Also the FSW process weld has NSR 4.54% (TIG) and 17.53% (MIG) higher than the corresponding processes.

The Tensile results confirm that the Friction Stir Welding process is higher in strength and gives better results. The properties implies that the fatigue strength of the metal increases with the welding with FSW process.

The Micro-Hardness weld line produced from the different welding processes and the Base metal are compared with each other. The Base metal has the lowest hardness in value following next by the FSW processes. The MIG process has the high hardness with TIG process between the MIG and FSW process. The FSW process has the highest relative hardness to the BM. The less heat produced causes less hardness and high life of the metal.

The Fatigue test shows that the number of cycles for the different welding processes is different. The FSW process has the highest number of cycles next to the Base Metal. The MIG and TIG process have lesser number of cycles than the FSW process. For the Notched joints the FSW process has about 88.88% of the life of the Base Metal. The TIG process has 77.7% and the MIG process has 66.6% of the life of the Base metal. The FSW process shows 11.11% increase over TIG and 22.2% increase over MIG process.

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