Fatigue analysis of the friction stir welded AA6061-T6 aluminum alloy

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Abstract
Investigation of mechanical and fatigue behavior is necessary to find out the long-term durability of the welded joints. The current work focuses on the mechanical and fatigue behavior of the joint formed when AA6061-T6 alloy plates were friction stir welded (FSWed) then joint was also analyzed as compared with parent material. The tensile strength and microhardness profile were obtained by the uniaxial tensile test and Vickers hardness test respectively. The maximum yield strength and ultimate tensile strength of the FSWed specimens were found to be 207.2 N mm\(^{-2}\) and 264 N mm\(^{-2}\) which are 72.2% and 80.3% of the parent metal respectively. The minimum value of hardness in FSWed specimen was equivalent to 63% of the parent material. The fatigue tests were carried out in a constant amplitude loading condition at a positive load ratio \((R = 0.1)\). The limit of maximum stress applied during the fatigue tests was determined based on the results of the tensile tests. Microstructural and scanning electron microscope (SEM) examination of welded specimens was also carried out to understand the effect of FSW on microstructural development, commence of fatigue crack, and the way the crack spreads. The outcomes show the formation of a fine-grained microstructure in the center of the weldment. Results of the fatigue tests show that the fatigue strength of both types of configurations i.e. FSWed and parent material were almost the same at the low-stress level. At high-stress level, parent material exhibits superior fatigue strength than FSWed specimens. An effort has also been made to relate the fatigue resistance to the microstructural observations of the welded specimens.

1. Introduction
Welding allows the production of material parts which are difficult to be formed by other manufacturing processes. Demand for complex shape products that cannot be manufactured in one unit or are too costly is increasing rapidly due to advancements in production technologies. Also, the industrial use of alloying materials has increased a lot in the last decade as it enables us to get the desired properties of different elements together. Friction Stir Welding (FSW) is one such process that was evolved for welding soft metals that difficult to be weld by different traditional welding processes. In the past 20 years, the process of FSW may be considered as an important development in the field of welding technologies for joining similar or even dissimilar workpieces [1–5]. FSW can be considered as a solid-state welding process because no significant melting occurs, so provides lower distortions in the weld. FSW can provide the welds of better quality because the surface defects like shrinkage, porosity, oxidation, and solidification cracking which are common in other fusion welding techniques are less developed [6, 7]. But, sometimes tunneling and kiss bond defects could be present [8]. Metals and alloys having low melting points like aluminum or magnesium can be weld easily by the FSW technique. Because of these benefits, FSW is now extensively used in various manufacturing industries such as high-speed
train manufacturing industries (railway coaches), shipbuilding (storage vessel), aerospace industry (wings and fuel tanks), automotive industries, and construction industries [9, 10].

A lot of earlier studies have been done by researchers that improved mechanical properties and fatigue strength can be achieved by the FSW process when compared to welds produced using other welding processes [11]. Later, researchers have been focusing on joining different materials or alloys through the FSW process. Work in progress is now focused on optimizing the FSW technique to weld dissimilar alloys that are very far apart [12]. Parameters that most influence the microstructural and fatigue behavior in FSW are rotational and transverse motion, tool geometry, and plunge depth which have also been widely investigated for different materials by the researchers. Moshwan et al [13] studied the microstructure behavior of FSWed AA5052 alloy. They kept welding speed constant but varying the tool rotation speed from 800 to 3000 rpm during the welding process and they found out from the results of experiments that the highest yield strength of alloy was found at a rotational speed of 1000 rpm. Lakshminarayanan and Balasubramanian [14] investigated the impact of different FSW parameters such as tool rotational speed, axial force, and traverse speed on the mechanical behavior of Al-Zn-Mg alloy. The Taguchi method was also used to find out the optimum values of the process parameters. Their conclusion states that these parameters have a noteworthy effect on the tensile strength of FSWed joints. Hamilton et al [15] have worked out the FSW of AA6082 alloy and investigate the effects of different tool geometries on the micro and macrostructure behavior of the welded joint. The results show that the double-sided welds having weaker mechanical properties when compared to single side welds because of the more heat transference to the material. Furthermore, different experimental methods as well as numerical simulation techniques have been used by several researchers to detect residual stresses during FSW process. Cho et al [16] used the finite volume method under the steady-state condition to perform a thermomechanical simulation of FSW process for ferritic stainless steel. Zhang [17] and Dialame et al [18] used thermo-mechanical analysis and Eulerian formula for simulation of the FSW process of aluminum alloys.

To prevent failure of the mechanical components subjected to fluctuating load conditions it becomes necessary that the maximum stress enforced should be less than the ultimate tensile strength of that component. The majority of failures in materials subjected to cyclic loading are due to a progressive degradation mechanism called fatigue. So, it is important to analyze the phenomena of fatigue failure in such materials. Fatigue failure in engineering materials is considered as the combination of crack development and its growth mechanisms. The main reason for crack development in the material may be the presence of discontinuity at the microscale level. The quality of FSW is also one of the main reasons that affect the fatigue strength. Dickerson [19] investigated the fatigue behavior of FSW specimens. Some specimens had defects and other was defect-free. Results show that FSW joints with no defects remarkably have better fatigue performance than conventional fusion welds. Ericsson and Sandstrom [20] investigated the fatigue behavior of FSWed joints of materials that are used in the automobile as well as aircraft industries. Wen Wang et al [21] analyzed the fatigue performance of FSWed AZ31 Magnesium alloy plate with different tool rotation speeds. Their results showed that by reducing the rotation rate, the grain gets refined, while there is a slight change in the texture in the stir zone (SZ). The fatigue fracture occurred at the SZ boundary owing to grains coarsening. Fatigue failure is a complex phenomenon and therefore fatigue strength of a material cannot be fully established. In recent years, several attempts have been made to find out how different FSW parameters affect fatigue behavior. Robert Kostrurek et al [22] studied the fatigue properties in FSW of AA2519—O joint. The lowest value of hardness was found at a distance of 10 mm from the center of the nugget zone. This low stiffness zone can be considered important for fatigue crack initiation. Kim et al [23] studied the fatigue strength of AA6005-T5 alloy plates. They used gas metal arc welding (GMAW) and FSW techniques for welding. They found that the fatigue behavior was superior in FSW joints than the joints fabricated by the GMAW technique. Also, it was established that if both tool rotation and welding speed increased during FSW, fatigue resistance was considerably reduced. Chowdhury et al [24] study the microstructural changes of FSWed joint of AZ61 magnesium alloy under different process parameters and proved that tool profile and tool rpm are the two parameters that affect mechanical properties the most.

In this paper, an effort is made to investigate mechanical properties as well as fatigue behavior of AA6061-T6 alloy welds by FSW. The vertical milling machine was utilized for the fabrication of welded joints.

2. Experimental procedure

AA6061-T6 alloy plates of thickness 6 mm have been used for the present investigation. This alloy is used in wide applications in industries due to its low cost and lightweight. The elemental composition of the alloy used is given in table 1. To achieve the T-6 condition, the material was subjected to an artificial ageing process and the temperature in the range of 185 °C—190 °C was maintained. The plates used for FSW were cut into a rectangular shape of dimensions 150 mm × 100 mm. The two plates were welded as a butt joint as shown in figure 2. H13 steel tool with a cylindrical grooved pin profile having diameter of 5 mm was used for the FSW process. The
shoulder to pin ratio is kept equal to 3.1:1. FSW joints have been fabricated by using the vertical milling machine with a suitable fixture arrangement. The welding parameters such as welding speed of 250 mm min⁻¹, the tool rotation speed of 1200 rpm, and a tilting angle of 2° were implemented. The whole setup and tool pin profile used for FSW is shown in Figure 1.

To examine microstructural behavior, the FSWed samples were polished properly using different grits of emery paper (i.e. 600, 1000, and 1500 grit size) and then etched by Keller’s reagent for 5 min at room temperature. The reagent has the following composition: 0.2 ml HF, 0.3 ml HCL, 0.5 ml HNO₃ and 95 ml distilled H₂O. Then the etching specimens were washed with water and ethanol (C₂H₆O). Finally, the optical microscope at 10X magnification has been used to investigate microstructural properties and homogeneity of welded joints.

To evaluate the microhardness profile, Vicker’s hardness test was conducted on cross-section of specimens. The indentation load used was 250 gf with a dwell time of 10 s. The hardness profile was taken for the middle cross-section of welded samples. Starting from the center, the microhardness profile was estimated on either side of the weld. Specimens for tensile testing were prepared and all tests were performed at an ambient temperature according to ASTM E8/E8M-16a1 guidelines. It was also noted that the welding stir zone should be located in the middle. An extensometer was used for measuring the deformation that takes place in specimens. The tensile specimens were tested until fracture to evaluate macroscopic properties such as yield strength (YS) and the ultimate tensile strength (UTS). Three different specimens of both materials configuration (parent and FSWed) were taken for the tensile test whereas, for hardness measurements, a single specimen of both parent and FSWed

| Weight% | Al  | Mg  | Si  | Cu  | Fe  | Cr  | Mn  |
|---------|-----|-----|-----|-----|-----|-----|-----|
| AA6061-T6 | Bal | 0.91| 0.59| 0.21| 0.19| 0.16| 0.08|
material was used. The values of these properties were used to define the limit of maximum stress that can be applied during fatigue testing of specimens.

To analyze the fatigue behavior of parent and welded specimens, load-controlled fatigue testing was carried out at Instron-8801 servo hydraulic fatigue testing machine having load cell capacity of 100 kN. The specimen of dog-bone/hourglass shape was prepared according to ASTM E466-15. The dimensions of the specimens were kept the same as the specimens of the tensile test as shown in figure 3. A load frequency of 50 Hz and a load ratio (R) of 0.1 was used. Seven dissimilar amplitude stress levels (i.e. \( \sigma_a = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \)) ranging from 63 to 90 N mm\(^{-2}\) were selected to draw the fatigue lifetime versus amplitude stress curve. The highest stress level chosen was lower than the YS as given in table 3. For FSWed specimens, the range of applied stress was equivalent to 68% to 96% of the YS\(_{\text{joint}}\) whereas, for un-welded specimens, the range is equal to 49% to 70% of the YS\(_{\text{PM}}\). For each stress value, the test has been repeated a minimum of three times.

Sufficient samples of parent material were also made for comparison. The geometry of each sample was accurately measured before each test. The number of cycles considered as a threshold for infinite life was 10\(^7\) cycles. The sequence of the tests performed is shown in table 2.

### 3. Results and discussion

#### 3.1. Microstructure behavior

A sample of the joint created by the FSW process is shown in figure 2. The joint formed consists of different zones named as stir zone (SZ) or nugget zone (NZ) within the center, thermo-mechanically affected zone (TMAZ) on each side of SZ, heat affected zone (HAZ) adjacent to the TMAZ, and parent metal (PM) (figure 4) [25, 26]. No severe defect was found in the joint when physically investigated.

In the present investigation, a metallurgical microscope with a magnification power of (10X) is used to analyze the microstructure behavior of the FSWed joints as shown in figure 5. The weld seams showed a smooth and clean surface and no welding defects such as porosity and voids were found.
Figure 5 shows details of the dissimilarity of microstructure related to different zones suggested in figure 4. SZ can be distinguished separately because of the recrystallized fine-grained structure. One reason for this is that microstructure forms through dynamic recrystallization during the stirring process. The width of the SZ depends on the combination of tool design, welding parameters, and alloy composition. The grain size increase from the weld nugget as we move towards the HAZ. Non-identical grains were also found when moving from the upper side to the bottom side in SZ. The ordinary grain size on the bottom side of the weld was found to be smaller compared to the middle and upper side. This is often because more heat is generated within the upper surface of welded material due to complete contact with the tool shoulder during the welding process. The bottom side of the welded specimen, on the other hand, is attached to the backplate. As a result of which the rate of cooling on the bottom side of the welded specimen will be high and resulted in a faster recrystallization process. Due to the slow cooling rate on the upper side, more time is available for the recrystallization process. A quantitative relationship has been established because the nature of grain boundary influences the moment of grain boundary slidings. Figure 5(a) shows high fraction of high-angle grain boundaries. It may occur in the SZ due to a high tool rotation speed of 1200 rpm. The aspect ratio was found to be around 2.04.

After completion of the FSW process, there is a zone known as HAZ in which the microstructural changes occur only due to the heating effect and not by the interference of mechanical forces. There is another zone present between HAZ and SZ known as TMAZ in which the effect of both heating and mechanical forces was liable for the changes in microstructural properties. The microstructure was found to be highly deformable in TMAZ. The dynamically recrystallized phenomenon does not complete in both TMAZ and HAZ during FSW process, but the smaller precipitates have coarsened during the welding process.

3.2. Mechanical behavior
The tensile test results are shown in table 3. The yield strength (YS), as well as ultimate tensile strength (UTS) of FSWed specimens, are found to be less than the parent material. The average YS of the FSW joint was 207.2 N mm$^{-2}$ which was equivalent to 72.2% of the parent material YS. Similarly, the average UTS attained by welded and un-welded specimens was 264 N mm$^{-2}$ and 328.9 N mm$^{-2}$ respectively. The UTS of welded joints is 80.3%
### Table 3. Tensile test results.

| Specimens              | Yield strength, YS (N mm$^{-2}$) | Ultimate tensile strength, UTS (N mm$^{-2}$) | Elongation (%) |
|------------------------|----------------------------------|---------------------------------------------|----------------|
|                        | Average value | Standard deviation | Standard error | Average value | Standard deviation | Standard error | Average value | Standard deviation | Standard error |
| AA6061-T6 Parent material | 287          | 1.7               | 0.157          | 328.9        | 1.4               | 0.071          | 10%           | 2.3              | 0.139          |
| AA6061-T6 FSW configuration | 207.2        | 3.1               | 0.201          | 264          | 4.1               | 0.191          | 4.7%          | 5.8              | 0.267          |
lower in comparison with UTS of parent material. Also, the ductility of the welded specimen was found to be less than the parent material. Failure of all tensile test specimens was found within the HAZ region.

The Vickers microhardness profile is obtained for FSWed specimen is illustrated in figure 6. Due to the appearance of fine grains structure more uniform distributed hardness profile was observed in the SZ. It has been observed that the maximum amount of heat is created in HAZ during the welding process and so HAZ is the softest zone in the FSWed specimens. For parent material, the microhardness value was found to be 96 HV. The average minimum hardness in welded specimens was equivalent to 63% of the parent material. The standard deviation and error value for the FSWed specimens were found to be equal to 2.6 and 0.098, respectively. Despite the lower hardness value, the SZ showed reasonable joint strength.

Intense plastic distortion takes place during the process of FSW. The inter-material is stirred and the grain refinement takes place because of the dynamic recrystallization during the stirring process. The grain size increase from the weld nugget as we move towards the HAZ. During microstructure analysis, it was found that the grain coarsening has taken place in HAZ. Also, in heat treatable aluminum alloy like AA6061, the precipitates of Mg2Si are responsible to enhance the strength of the alloy [27]. The precipitates dissolve to a large extent during FSW process which further reduces the mechanical strength of FSW joints. The dissimilarity in hardness value can be attributed to the dissolution of the precipitate and grain size during FSW process [28, 29]. Some researchers have also investigated that the hardness of aluminum alloys was preferably affected by precipitate distribution and not because of grain size in the weld [28].
3.3. Fatigue behavior

Figure 7 shows the effect of fluctuating loading in terms of the S–N diagram on the fatigue strength of FSWed and parent materials. We can get many important observations. As expected, at a higher stress value, both types of specimens will fail at less number of cycles. The results obtained in the graph are very scattered and hence, no definite value of fatigue life can be stated for both material configurations. Some samples of the parent and the welded materials did not fail at the lower value of amplitude stress (recognized as run-out tests); hence $10^7$ cycles were taken as a threshold value for infinite fatigue life. For welded specimens, it was found that fatigue life can be considered infinite at a value of 62% to 68% of the yield strength. To further estimate, data of specimens that did not get break down during fatigue testing as well as doubtful results were all omitted from the investigation. The remaining results were also shown by the linear fitting curve.

The stress cycle diagram also shows that the fatigue strength of the FSWed material was approximately comparable to the parent material at low-stress amplitude values. But at relatively high amplitude stresses, the fatigue strength of the parent material was found to be higher than the welded material. The failure site in the welded material was also another important point. Experimental results show that at low-stress amplitudes i.e. $<76.5 \text{ N mm}^{-2}$, the FSWed specimens failed in the PM zone despite that this section shows the higher strength value. In contrast, at high-amplitude stresses, failure under cyclic loading occurs in the HAZ region. This is the softest region as per microhardness measurements.

3.4. Fatigue fracture analysis

The fracture surface of the fatigue specimens was also investigated to obtain additional information on fatigue behavior. Two cases were examined, including (i) the weld specimens failed in the parent material section at relatively low stress and (ii) the weld specimens failed in the heat-affected zone at relatively high stress. It has been observed that the fatigue failure of the specimens was affected by different parameters such as precipitation, coarse grain size, grain boundaries, and aspect ratio. The homogeneous fracture will be dominated by the correlation of these factors. To investigate the normal fracture process for parent and FSWed material, the evolution of microstructure near the fracture point was analyzed.

In both cases, the fractured surface could be considered as complicated, involving two different domains. One of these domains was comparatively smooth hence signifying brittle fracture in the material. Another domain was characterized by well-developed surface relief which is the indication of ductile failure. Three distinct characteristic sections were also noticed including crack initiation (Stage I), crack propagation (Stage II), and fracture (Stage III).

Figures 9(a)–(d) shows the macrographs of a specimen that fractured in HAZ under high amplitude stress. It has been shown that the crack started in the HAZ and propagated up to failure. In this zone, second and third cracks were also observed. This may occur due to the presence of precipitate hardening in HAZ. In some instances, crack initiation point and crack propagating zone are observed in parent material at low-stress
amplitude as shown in figures 8(a)–(d). In this case also crack initiation and propagation took place in parent material itself.

Mostly, crack nucleation was taking place on the free surface of fatigue specimens which may be instigated by a sharp corner, a notch, or a hole shown in figures 8(a) and 9(a). Due to the presence of a few small cracks simultaneously, the presence of ratchet marks was noticed in the crack initiation section. The fracture surface formed by Stage I was signifying that the slow crack growth possibly occurred by the intrusion-extrusion mechanism (figures 8(b) and 9(b)). The commanding slip plane leads to the development of metal extrusions on the planes where dislocations approach a free surface.

Minor grooves were also found on the fractured surface during stage II (figures 8(c) and 9(c)). These minor grooves are known as fatigue striations and are responsible for an irregular propagation of fatigue crack in the material. The position of these grooves was found perpendicular to the cracks. The existence of striations on the surface shows that fracture was instigated by fatigue. If the striations are not appearing, then it cannot be inferred that the fracture is not caused by fatigue. In this investigation, striations are not found on the entire fractured area, yet with the help of these, it is common to detect areas where the fracture mechanism is not well defined. The fractured surface was found comparatively flat during Stage I and II. It signifies the brittle characteristic of the failure.

In stage III of fatigue failure, the microscopic voids with oval traces are seen on the fractured surface. These voids are attributed to the ductile fracture (figures 8(d) and 9(d)). Their texture resembles that of small craters or dimples on a fractured surface. The size of these voids is straightly associated with the size and dispersion of the second phase particles.

In the fracture examination, no main differences were found between the studied samples. This meant that the mechanism of crack nucleation and propagation was almost similar in all cases. A significant observation in this study also came out that there was not much resistance to crack propagation.

4. Concluding remarks

FSW with welding parameters as welding speed of 250 mm min$^{-1}$ and 1200 rpm tool rotation speed is used to weld AA6061-T6 alloy plates under normal environmental conditions. Physically verification shows that the weld is free from any major defect.

A fine grain structure was found in SZ. The grain size increase from the weld nugget as we move towards the HAZ on either side of the weld. During microstructure analysis, it was found that grain coarsening has taken place in HAZ.
In the tensile tests of FSWed as well as parent material specimens, the YS and UTS are found to be lower for welded specimens. All the welded specimens were failed in the HAZ region during tensile tests. The detailed hardness examination revealed that the SZ exhibit a uniform hardness profile. The results obtained show that the minimum hardness value is found in the HAZ.

During fatigue tests, different levels of amplitude stress were used. According to the results obtained, it is found that the fatigue strength of FSWed specimens is almost equal to that of parent material at low amplitude stress levels. At higher amplitude stress levels, specimens of parent material exhibit superior fatigue performance than FSWed materials.

At low amplitude stress, the specimens fabricated by FSW failed in the parent material zone whereas, at comparatively high amplitude stress, fracture commonly occurred in HAZ. The S-N diagram also shows that the obtained results are more scattered in the case of welded materials than for parent materials.

It is revealed that fatigue damage at high amplitude stress in HAZ is due to the precipitate hardening during the FSW process. One thing to note here is that SZ exhibits a very fine grain microstructure, yet no sample has failed in this zone.

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