Fatigue behavior and fractography in friction stir welding zones of dissimilar aluminum alloys (AA5086-H32 with AA6061-T6)

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Abstract. Dissimilar aluminum alloys of AA5086-H32 with AA6061-T6 were welded by friction stir welding method using three different values of linear and rotating speed; V= 50, 75 and 90 mm/min., N= 680, 920 and 1500RPM. Tensile test was used to determine the efficiency of welded samples. The microstructure, hardness, XRD analysis and fatigue tests were studied for the welded sample with the highest tensile strength. The fatigue test was studied in the welding and the nearby region at a distance of x=5, 10 and 15 mm from the welding line. The fractured fatigue surface was analyzed using SEM. The welding speed used has an effect on the efficiency of the welded samples where the maximum welding efficiency (82%) was obtained at N= 680 and V= 75 mm/min. The microstructural analysis indicated that there is a significant elongation and bending in the grains of the thermo-mechanical affected zone (TMAZ) in the advance side (AA5086-H32) of the weld compared to the retreating side (AA6061-T6). The results of XRD and EDS indicated that there is no transition of phases between the two alloys. The maximum value of hardness was at the weld line and started to decrease away from it, hence the values of hardness at the advance side was higher compared to the retreating side. Fatigue strength of the welded samples was less than the wrought alloys.

Keywords: frictions stir welding; dissimilar aluminum alloys; fatigue properties; microstructure

1. Introduction

Aluminum alloys have properties such as good strength, light weight and corrosion resistance that make it used in most parts of structures [1]. The aluminum alloys AA5xxx and AA6xxx used in the ship, aircraft and transport vehicle structure fabrications [2, 3]. Welding of these grades of aluminum alloys by means of gas tungsten arc welding or gas metal arc welding processes result in welding problems due difference in solidification modes for each type of alloy, and therefore, the friction stir welding (FSW) process was considered as a good method to weld different aluminum alloys [4-6]. This process is a solid state welding technique [7-10].

The fatigue behavior of friction stir welded of different series aluminum alloys (1050, 5083, 6061 and 7075) was investigated by Uematsu et al. They concluded that the fatigue behavior was sensitive to the
microstructures of the welding zones. The fatigue strengths of the welded samples were equal to or lower than those of the parent materials [11]. In another work, the fatigue behavior of dissimilar FSW joints of different aluminum alloys (AA6082 with AA5754) was studied by Infante et al. The fatigue stress ratio was R=0.1. It was observed that the fatigue strength of the welded joints was less than those of the base material. The improvement in the fatigue strength was observed for lower applied stress ranges [12]. The axial fatigue strength of dissimilar joints between AA2124 and AA2024 by means of FSW was achieved. The analysis of the fracture surfaces was investigated by SEM. Good fatigue properties were observed in the joints compared to that of the base material AA2024. The fractured region was located in the region of thermo-mechanically affected zone TMAZ or in the weld center. [13]. Dissimilar aluminum alloys type 5083-H111 and 6082-T651 were welded by FSW and tested by the bending fatigue. The thickness of each plate was 6mm, the welding machine parameters were: 1250 rpm rotating speed, 64 mm/min travel speed and 2° tool tilt angle. The results showed that the fatigue strength of joints was close to each other with small void effect [14]. Fatigue crack propagation of was investigated for the dissimilar aluminum alloys joints 6061-T6 and 304 stainless steel welded by FSW. The results showed that the rate of fatigue crack propagation of the welded joints were comparable or slightly faster as comparing with the base material of aluminum [15].

The effect of FSW process parameters on the formation of welding defects of dissimilar aluminum alloys: AA5083-H116 and AA6063-T6 were investigated. The tunnel defects were found in the advanced side. The kissing bound were formed towards the retreating side [16]. The microstructure of FSW joints of AA6061 and AA5086 were studied. The microstructure investigation indicates that the hardness of joints was improved due to brittle intermetallic phase formation and higher fraction of grain boundary [17]. A lap joint of AA 6082-T6 with AA 5754-H22 was performed using FSW. They concluded that the hooking defects were the major factor that affect on the tensile strength of the welded joints [18]. Dissimilar aluminum alloys AA2024-T3 to AA7075-T6 were welded by FSW. The effect of welding process parameters on the mechanical properties of joints was investigated. During the welding process no material mixing was observed. The grain size of each material has two different sizes [19]. Aluminum alloy type AA6181-T4 was welded with high strength steel. A similar microstructure development was observed in each material. The tensile strength efficiency depended on input heat and the TMAZ of the aluminum alloys [20]. FSW of different aluminum alloys 2014-T6 to 6001-T6 were performed taking into account the effect of various welding process parameters. It was found that the percentage of each alloy in the stirred zone (SZ) affect on the metal flow, hardness, temperature distribution and the welding torque [21]. The mechanical properties and microstructure of the FSW joints of AA6061 to AA7050 were studied. A similar hardness profile distribution was observed about the weld line. This was due to the distinct properties for both alloys. Increasing the rotating speed resulted in increase the joint strength. The first sets of welded specimens were failed in the stirred zone due to the inadequate material intermixing. The other was failed at the HAZ due to the material softening [22].

Muna et al. [23] in 2016 used the Taguchi method to optimize FSW parameters (rotation speed, welding speed and tool design) for dissimilar aluminum alloys (AA2024T3 to AA7075T73 ). From ANOVA for the tensile strength result, they concluded that the welding speed was the most significant parameter with a percentage contribution of 66.05 % over the other process parameters. Muna et al. [24] performed precipitation hardening treatment and post weld aging to improve the mechanical properties of similar friction stir welded joints for AA2024-T3 and AA7075-T73. The results showed that the best aging conditions for similar welded joints of 2024 and 7075 was in sample at condition (natural aging for two week) and sample at condition (artificial ageing at 120°C for 24 h) respectively.

The present work objective is to study the effect of the linear and rotational speeds of the welding machine on the tensile strength of the welded aluminum alloys type AA5086-H32 to AA6061-T6. The metallurgical and fatigue properties of the welded sample which gave the highest tensile strength were analyzed.
2. Experimental Work

2.1. Materials

The materials used in the friction stir welding process are two types of aluminum alloy; AA6061-T6 and AA5086-H32. The chemical compositions of each material were determined using x-ray fluorescence (XRF) method. Three tests were performed for each material such that the average values was calculated and listed in table 1.

| Table 1. Chemical compositions of AA6061-T6 and AA5086-H32 |
|-----------------|-------|-------|------|-----|----|----|----|----|-----|
| Element wt %    | Si    | Fe    | Cu   | Mn  | Mg | Cr | Ni | Zn | Ti  | Al  |
| AA5086-H32      | 0.06  | 0.28  | 0.07 | 0.47| 3.72| 0.1| -  | 0.06| 0.01| Rem.|
| AA6061-T6       | 0.677 | 0.429 | 0.309| 0.067| 0.872| 0.2| 0.01| 0.112| 0.017| Rem.|

The standard (ASTM B557M-02a) was adopted for the manufacture of tensile test samples for the purpose of examining the mechanical properties of each material. The schematic and photographic shape of a manufactured tensile test sample was shown in Figure 1. Tensile test results were listed in table 2.

| Table 2. Tensile test results of AA5086-H32 and AA6061-T6. |
|-----------------|-------|-------|------|
| Material        | Yield stress (MPa) | Tensile stress (MPa) | Elongation (%) |
| AA5086-H32      | 221   | 325   | 8.5  |
| AA6061-T6       | 284   | 348   | 8    |

2.2. Preparation of welding process

A butt joint of dissimilar friction stir welding was produced from two plates of different materials; AA5086-H32 and AA6061-T6. The dimensions of each plate were 3x100x200 mm. The welding direction was perpendicular to the rolling direction. The tool used in friction stir welding is of type oil hardening tool steel (ASTM A681-94 O1 type). This tool consists of two cylindrical parts: the first represents the pin and the second is the shoulder. Before starting the welding process, the samples were fixed using fixture and backing plate tied to the base of the milling machine as shown in Figure 2. The weld line length was 200 mm.
2.3 Welding process parameters

The parameters of the welding machine which can be manually controlled include travelling and rotational speed as well as to tilt angle of tool. These parameters have a significant effect on the quality of the final product of the welded samples. The mechanical, metallurgical and microstructural properties of the weld, heat affected and thermo-mechanical affected regions change by changing these parameters. The optimum properties of a weld can be obtained by experimenting with a wide range of variables that possess the most influence (rotational and linear speed). Increasing the rotational speed and reducing the linear speed leads to increased heat generated by the friction between the sample and the welding tool depending on the roughness of the surface. In order to obtain good welding properties, the generated heat must be sufficient to plasticized the material around the tool, while, the high input heat leads to produce weld defects [25].

In this research, three values were used for both rotational and linear speed. Table 3 presents the welding speed values used for welding samples. The welding process has been achieved using butt arrangement of the joint configuration with one side and one pass of welding. Analysis of fatigue in friction stir welding regions of AA5086-H32 to AA6061-T6 aluminum alloys

| Sample No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|------------|---|---|---|---|---|---|---|---|---|
| Linear speed (mm./min.) | 50 | 75 | 90 | 50 | 75 | 90 | 50 | 75 | 90 |
| Rotation speed (RPM) | 680 | 680 | 680 | 920 | 920 | 920 | 1500 | 1500 | 1500 |

Friction stir welding performed in four stages: plunging, penetration, stirring and end of welding as shown in Figure 3-a. The welding line divided into two sides. The side where the linear and rotating speed are in the same direction represents the advancing side. While the aspect in which the linear and rotational speeds are opposite direction represents the retarding side [25] as shown in Figure 3-b.
2.4 Tests of Welded Samples

2.4.1. Nondestructive testing

Visual inspection is the first diagnosis of the defects of optical welding surface of the naked eye like misalignment, flash and lack of penetration. The second test is an X-ray radiographic inspection that is used to examine all internal defects in the weld. The microstructure and x-ray diffraction tests were used for the purpose of clarifying the change in the microstructure of the weld metal, thermo-mechanical affected and heat affected zones.

2.4.2. Destructive testing

The tensile test was performed for all welded samples according to the AWS D17.3/D17.3M:2010. This standard is considered as a more accurate for testing of the FSW samples compared to that of the base material (ASTM B557M-02a). The tensile test samples were manufactured such that the welding line is located in the middle of the sample as shown in Figure 4.

The second destructive test which was adopted to study the mechanical and metallurgical properties of weldments represents the fatigue test. The weld conditions (linear and rotating speed) that gave the highest ultimate stress value in tensile testing were approved for the manufacture of fatigue test samples. The fatigue behavior of the sample was studied in different regions, such as welding line, heat affected zone (HAZ), and thermo-mechanical affected zone (TMAZ) and the base material.

The fatigue test used is the type of alternating bending test. Samples of this test were manufactured as shown in Figure 5. The behavior of the highest fatigue bending stress was studied in four regions (x = 0, 5, 10 and 15 mm). The fractured surface of the fatigue sample was studied using Scanning electron microscope (SEM).

Vicker micro-hardness test have been performed at different points; weld region, HAZ and the TMAZ. The load and duration time of the micro-hardness tests were 1.96N and 10sec. respectively.
3. Results and Discussion:

3.1. Welding defects

Friction stir welding occurs by mixing the solid state metal due to the high heat generated by the friction of the tool with material. This leads to produce internal and external defects during the welding process. When the heat generated during the welding process is not enough to mix the materials, this leads to these defects. Three types of defects were found on the welding surface: flash, sound and incomplete weld line. In addition, three types of defects were observed in the cross sectional area: tunnel, void and incomplete coalescence.

Internal welding defects were observed through X-ray radiography inspection. Figure 6 shows the results of this examination. It was observed that the welded samples at low speed (N= 680 RPM and V= 50 mm/min.) do not contain internal defects as shown in Figure 6 (a, b and c). On the other hand, because of the high heat generated during welding at high speed, defects such as incomplete coalescence, small crack line in end hole and surface defect are observed as shown in Figure 6 (d, e and f) respectively.

3.2. Tensile test

The tensile test results showed that all welded samples had failed in the welding region. This can be attributed to the change in the mechanical and metallurgical properties of both metals during the welding process. Figure 7 shows the tensile test results and model of a fractured sample in the welding region. The sample numbers shown in this figure are the same as those listed in the table 3. The highest values of tensile strength and efficiency were observed at low and high rotational speeds (N= 680 and 1500 RPM) regardless of linear welding speed. The intermediate rotational speed (N= 920 RPM) gave the lowest values of tensile strength. Maximum welding efficiency (82%) was found at a lower rotational speed (N= 680 RPM).
680 and \( V = 75 \text{ mm/min.} \)). It is worth mentioning that the linear welding speed also has an effect on welding efficiency. Where the highest welding efficiency was observed at the intermediate linear speed (\( V = 75 \text{ mm/min.} \)) in the case of the use of the lowest and the highest rotational speed (\( N = 680 \) and 1500 RPM) respectively. On the other hand, minimum welding efficiency was observed at the same linear speed (\( V = 75 \text{ mm/min.} \)) in case of intermediate rotational speed (\( N = 920 \) RPM).

![Figure 7. Tensile test results (a) tested specimen (b) tensile strength (c) efficiency of tensile strength](image)

3.3. Microstructure analysis

The microstructure of the welded sample at weld conditions (\( N = 680 \) RPM, \( V = 75 \text{ mm/min.} \)) which gave the highest tensile strength were illustrated in Figure 8. This figure represents the welded joints of two different aluminum alloys; AA5086-H32 and AA6061-T6. The first (AA5086-H32) is located on the left and represents the advancing side. The second (AA6061-T6) is located on the right side and represents the retreating side. In general, the friction stir welded section includes four zones as shown in Table 4.

**Table 4. Regions of welded section**

| Region                          | Location                  | The descriptions                       | Figure (9) |
|---------------------------------|---------------------------|----------------------------------------|------------|
| Nugget zone (NZ)                | in the center of weld     | fully re-crystallized                  | b and f    |
| Thermomechanically affected zone (TMAZ) | at both sides of NZ | affected by heat and deformation       | c and g    |
| Heat affected zone (HAZ)        | between TMAZ and BM       | affected by heat with no plastic deformation | d and h    |
| Base metal (BM)                 | Next to the HAZ           | –                                      | a and e    |

The microstructure of the base materials for both of AA5086-H32 and AA6061-T6 is shown in Figure 8 (a and e) respectively. The microstructures of the heat-affected zone in the advancing and retreating sides; Figure 8(d and h) are approximately similar to that of base materials without any significant in grain coarsening.
The TMAZ is shown in Figure 8 (g and c) for the welded AA5086-H32 and AA6061-T6 respectively. It was observed that there is a clear and significant bent and elongation in the TMAZ grains at the advanced side as comparing with the retreating side. Hence, the plastic flow of material from the advance to the retreating side make a fiber structure pattern during the FSW process. In addition, the direction of the plasticized materials on the advanced side of the weld is the opposite of the base material, which leads to make the deformation and elongation of the grain is relatively large in that side. It is worth mentioning that the temperature in the retreating side (AA6061-T6) is lower compared to the advanced side (AA5086-H32), which makes the grain size in the retreating side fanner than the advanced side.

![Figure 8. The microstructures of the welded sample under different welding conditions](image)

3.4. XRD and EDS analysis

The XRD and EDS analysis of the welded sample at weld conditions (N=680 RPM, V=75mm/min.) were studied. The XRD results showed that there is a similarity between the parent alloy and the welded joint as shown in Figure 9. This is evidence that there is no depletion of the elements during the welding process. The reason is that the FSW is solid-state process [26] and that the temperature in the weld section is not sufficient to cause a transition in the phases. The EDS analysis showed the section of welding of the two alloys (AA5086-H32 and AA6061-T6) contains some elements such as (Mg, and Al-rem.) as shown in Figure 10.
3.5. Micro hardness Results

The amount of high heat generated during the friction stir welding process leads to refinement grain size and the occurrence of thermal changes in the weld zone [27], which in turn lead to a clear variation in the hardness as shown in Figure 11. It is noticeable from the figure that the highest value of the hardness (120HV) was found at the center of the weld region and decreases in the HAZ through the parent material of AA5086-H32 and AA6061-T6. This can be justified by the refinement and equaxed of grain in the stirred zone (SZ) and precipitation of second phase of Al₃Mg₂ and Mg₂Si from solid solution of Al-matrix during friction stir welding. These results were confirmed by XRD analysis. It was found that the values of the hardness of AA5086-H32 are lower compared to those of AA6061-T6 due to the softening process in HAZ region of AA5086-H32 side and coarsening and/or dissolution of strengthening precipitation during FSW.

Figure 9. XRD analysis of weld section AA5086-H32 with AA6061-T6 at N=680 RPM, V= 75mm/min.

Figure 10. EDS test of welding section AA5086-H32 and AA6061-T6 at N=680 RPM, V= 75mm/min.
These results are in agreement with results of researchers [28-30]. They used FSW process in welding similar and dissimilar aluminum alloys or metals under different conditions.

Referring to Figure 8, the fully re-crystallized zone gave the maximum hardness value which decreased gradually away from the center line of weld. Hence, the change in microstructure results in change in the hardness value of material.

![Figure 11. Microhardness of welding section AA5086-H32 with AA6061-T6 at N=680 RPM, V= 75mm/min.](image)

### 3.6. Fatigue results

Fatigue of welded samples was tested at optimum welding conditions, which gave the highest value for tensile strength. Therefore, all samples tested by fatigue test were manufactured according to welding conditions (N=680 RPM, V= 75mm/min). Fatigue test was analyzed in the welding region (x = 0 mm) and away from the welding line (x = 5, 10 and 15 mm) in the alloy AA6061-T6. The stress ratio used was R=-1. Figure 12 represents the fatigue test results for both aluminum alloys AA5086-H32 and AA6061-T6 and welded samples. Results showed that the efficiency of welded samples was lower than that of parent alloy. This can be attributed to the fact that the heat generated during the friction stir welding process led to a change in the mechanical and metallurgical properties. Also, the developed residual stress and plastic strains resulted in reduce the fatigue strength of weldments. The weakest fatigue properties were observed in the welding region (x=0 mm), which is exposed to the highest temperature during the welding process. Increasing the distance (x) means decreasing the temperature and as a result the residual stress and plastic strain will decrease. Therefore, the mechanical properties of weldment were approached to that of base material.
Figure 12. The fatigue test results for both aluminum alloys AA5086-H32 and AA6061-T6

The fractured surface of the welded section in fatigue test was studied using scanning electron microscope (SEM). In this inspection, the sample that failed at the number of $(1.6 \times 10^6)$ fatigue cycle under a bending stress of $(72 \text{ MPa})$ was studied. Figure 13-a represents the fatigue fracture surface for parent alloy 6061-T6. It was observed that a main crack starts from the specimen surface with some secondary cracks as shown in Figure 13-b. Another type of transverse crack and some of cleavage fracture surface facets were observed as shown in Figure 13-c.

Figure 13 shows SEM of fractured sample at 72MPa and $1.6 \times 10^6$ cycles for parent AA6061-T6

Figure 14 represents the main crack that started from the surface of the specimen AA5086-H32. The reason for the imitation of such a crack started at the edge of the sample is the concentration of stress which can be considered as stress raiser [31]. On the hand the Tran's granular fracture, fatigue striation and some secondary cracks at base alloy of 6061-T6 side were observed as shown in Figure 15. These results are in agreement to researchers Ahmed et al. [32].
4. Conclusion

The results showed that internal defects such as incomplete coalescence, small crack line in end hole and surface defects are formed during FSW welding of the aluminum alloys AA5086-H32 with AA6061-T6 which are depend on welding parameters (linear and rotational speed). This is due to high temperature produced by the high speed of the tool. Maximum welding efficiency (82%) is found at a lower rotational speed (N= 680 and V= 75 mm/min.). The linear and rotational speed of the tool affects the tensile strength hence the highest welding efficiency (82%) was obtained at the speeds: N= 680 and V= 75 mm/min. The advance (AA5086-H32) side showed a clear bent and elongation in the TMAZ grains as compared with the retreating side (AA6061-T6). The highest value of hardness was 120HV at the weld line. The
AA5086-H32 exhibited lower hardness compared to those of AA6061-T6. The fatigue efficiency of welded samples was lower than that of parent alloy. It was observed that the fatigue characteristics of the welded sample approached the parent alloy as moved away from the welding line. The fractography showed that the main reason for the fatigue failure of the welded sample is the presence of main, secondary and transverse cracks.

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