Research Article

Improvement of Mechanical Behavior of FSW Dissimilar Aluminum Alloys by Postweld Heat Treatments

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AA6262 and AA5456 alloys are welded through friction stir weld (FSW) with process parameters of tool speed of 1200 rpm, welding speed of 25 mm/min, and tool angle of 3 degree. A cylindrical shape HSS-13 tool is used to perform the welding process. To improve mechanical properties of tensile strength (TS), yield strength (YS), elongation%, hardness, and wear behavior, postweld heat treatment was conducted on the FSW sample at different temperatures from 300 °C to 500 °C. The influence of heat treatment (HT) changes the material characteristics. It is observed that the maximum TS (209 MPa) and YS (178 MPa) are identified when maintaining temperature 350 °C on the FSW sample. The reduction in elongation of as-welded joints is entirely improved by HT, and the elongation percentage is almost increased to 5% when increasing temperature on the heat treatment process, and hardness test results exhibited that the increased hardness value (120Hv) is found at HT-300 °C nugget zone distance of 0 to 5 mm range.

1. Introduction

Al6xxx and Al5xxx series are frequently used in a variety of fields, including the automobile, aviation, and aeronautical sectors because they have enough strength and corrosion resistance, producing fusion welding with enhanced mechanical characteristics and strong corrosion resistance on Al alloys, which is currently a major industry challenge. Several techniques such as liquid casting, powder metallurgy, and the FSW process are often used to create Al-based composites. The researchers have chosen an appropriate procedure among the above depending on the materials, material-reinforcement size, weight-ratio of the matrix, and purposes [1]. Fundamentally, FSW is a thermo-mechanical process that mixes the materials mechanically and thermally at the same time [2]. It was developed at TWI in the early 1990s, and it has already shown significant promise in combining materials that are typically thought of as difficult or impossible to weld [3]. Even though many of the welding techniques such as arc welding, gas welding, MIG, and TIG welding are available to join the dissimilar metals, many academicians and engineers from various businesses have focused on FSW dissimilar materials amongst Al alloys because the FSW process prevents joints from fusion defects and provides better strength than other welding techniques. The dissimilar joint properties primarily depend on the characteristics of the materials and input variables of tool and weld speed and locations of the joint, inequity of temperature, and material flow between the advancing and retreating sides [4, 5]. Ravikumar et al. selected three different shapeable tools (square, cylinder, and thread) to perform the FSW process on AA6061/AA7075 [6]. Trimble et al. have chosen a mixture of chosen parameters to generate welds and endurance at greater speeds using a T6 heat treatment experiment; various rotating speeds and tool speeds were employed in AA 2024-T3 research, and the
outcomes were better when the tool geometry had a scrolling shoulder and a tri-flute form for the pin [7]. Four-blade stirrers blade designs in CFD mostly improve tensile strength and hardness, as per Krishnan et al.’s [8] study on the effect of the design of stirrer blade on the mechanical behavior of AMCs. Delijaicov et al. identified the rotational speed andflowing rate as the most important variables that determine the heat input and material flow [9]. It has been established that changing the welding and rotating speeds reduces the hardness value in the stir zone between AA7075 and AA2024 by increasing rotational speed and reducing welding speed [10]. Hua-Bin Chen and colleagues investigated the FSW of 5456 Al under various circumstances. The plastic material was not flowing adequately and drives down nearby the pin end due to tool’s small tilt angle (less than 1.5). Weld flash produced where the plastic material is being treated, and not sufficient of plastic metal fill-up in a nugget zone was observed due to an increase in the tilt angle greater than 4.5° angle [11]. As per Goebel et al. investigation, HAZ and the border of TMAZ/SZ are extra prone to fail the thermal cyclesand give a partial precipitation in the HAZ, which is why it is weak, while residual stress causes weak bonding at the SZ/TMAZ contact [12]. Reddy et al. [13] analyzed FSW of AA7475-T761 plates, the welding centers, which has the finest microstructure, and exhibits the highest hardness value. Furthermore, according to their observations, the primary particles frequently generated in the SZ of AA7475 were Mg2Zn1, Al2Cu, and Al2CuMg. Under various welding conditions, creation of the dissimilar welded junction of Al5083–Al 6061(T6) was done; however, due to the dissolution of precipitation-hardening segments in the weld zone as well as the impact of the postweld heat treatment technique on the improvement of the mechanical properties of the dissimilar welded Al5083–Al6061 and leading abnormal grain evolution through various factors, softening behavior developed in the weld samples [14]. Baghdadi et al. directed to enhance the mechanical characteristics of Al-Mg-Si alloy through postweld heat treatment, the potential for regulating aberrant grain growth by adjusting welding conditions. The decomposition of precipitation-hardening particles in the HAZ was shown to have reduced the strength of the FSW samples in evaluation to that of the base material [15]. The UTS of AA6061-AA1100 and AA6061-AA5083 is 93 MPA and 113 MPa, respectively, after two types of dissimilar joints of these two alloys were joined using the FSW technique. In comparison to AA6061 base metal, the joint efficiency of AA6061-AA1100 and AA6061-AA5083 was 80% and 97%, respectively [16]. The FSW of AA6061 and AA1100 were studied by Jurnal Kejuruteraan et al. Welded samples were then cold rolled to various thickness reductions percentages of 10, 20, and 40%. Both the as-welded joints and the rolled specimens had no internal flaws visible from a microscopic examination of the sample’s cross section [17]. Addition of small amounts of powders B4C/CeO2 to the Al matrix was done in order to increase the weld ability of the AA2XXX and AA7XXX joints [18]. However, the most popular method for enhancing the strength and formability of the FSW sheets to the necessary level is solution treatment, and aging (SA) could rise the hardness and tensile strength due to precipitation hardening [19, 20]. After studying above literature articles, it was witnessed that few articles were discussed for the influence of various FSW parameters of weld speed and tool geometry to join dissimilar Al alloys for improving mechanical characteristics. Usually, weld strength depends on the heat generated and metal mixing during the FSW process [21, 22]. Even though the weld strength and mechanical properties are dependent on FSW parameters, but after welding, internal stresses on plates will affect the strength and properties of the joint heat treatment (HT) which is one important consideration to increase joint strength. So, in this research part, we introduced different heat treatment processes by variation of temperature which change hardness, tensile strength, and also wear rate, and this effort benefits to study the effect of heat treatment on FSW AA6262 and AA5456 alloys. The dissimilar welds of AA6262/5456 are useful in many application products such as hinge pins, marine fittings, screw machine products, pressure vessels, and storage tanks.

2. Material Selection and Experimental Procedure

AA 6xxx and 5xxx series alloys such as AA6262 and AA5456 plates are chosen to join with the FSW approach, and a plate size of 120*55*4 mm³ was preferred in the work. The compositions of each alloy are exposed in Table 1. The FSW process is carried out with the HSS 13 tool and possesses shoulder length* pin-length* pin size of 20*3.5*1.5. Three variables of tool rotational speed (FTR-1200rpm), welding speed (FWS-25 mm/min), and tool tilt angle (FTA-3 degree) are maintained. To perform welding operations, milling machine/FSW tools are fixed together, and the process of FSW schematic image is shown in Figure 1. The advancing and retreating sides are clearly mentioned in the FSW process figure. The plates 6262 and 5456 have grooves formed at their edges and are put over milling table with a clamp before operation begins. The specimens are gently penetrated with the spinning tool until the shoulder is 0.5 mm into specimen. The stated spot is fixed for 60 to 90 seconds in order to generate the required heat for the operation. Due to the production of heat at the weld location and the stirring caused by tool movement, the material enters the plastic phase, permitting the combination of the two metals. After the weld is finished, the machine setup is removed. The friction welded sample of both alloys 6262 & 5456 is shown in Figure 2. Once the FSW process is completed, the sample will go under various tests such as tensile, hardness, and wear test at different annealing temperatures or heat treatment (HT). In this work, total six HT conditions are preferred to check the weld strength and mechanical properties.

3. Mechanical Properties’ Test

3.1. Tensile Test. The unwelded AA 6262 exhibited YS and TS of 210 MPa and 285 MPa, whereas YS and TS values of AA5456 are 245 MPa and 320 MPa, respectively. Universal
A testing machine (UTM) is utilized to carry out the tensile test at room temperature. Before this particular test, we need to remove the sample from welded materials according to the standard size of ASTM-E08 in Figure 3. An extensometer (A50 grade) is attached with the specimen through the help of screw mechanism for calculating elongation after applying load on the specimen. This device is able to extend the length from 10 to 60 mm; the overall tensile properties results are displayed in Table 2. The fractured specimens for tensile test are exposed in Figure 4.

3.2. Hardness Test. A material’s resistance to a persistent indentation or marking by scratches is referred to as its hardness. Hardness is a value assigned to a material as a consequence of empirical testing and not a quality of the material itself. The majority of hardness tests involve the use of equipment that identifies the material while exerting a pre-defined force or loading. The hardness of welded composites can be found by making an impression of 1/16 indenter with 50 kg load on the surface of composites at different places on unwelded and welded areas. These experiments have been conducted on the hardness tester. The experimental works of hardness which are done by the hardness tester.

3.3. Wear Test. Wear test is performed as per standard ASTM - G99 by pin on disc device to find out the wear rate or wear amount of composites at different T6 heat treatments. Welded specimens were machined as pin shapes, and it was contacted on rotating steel by applying the load of 50N; sliding speed and distance are fixed as constant values of 2.25 m/s and 50 m, respectively. Before the start of the experiment, the composite’s sample weight is measured. During the process, the material is removed due to friction between the rotating disc and sample and the difference in weight after completion of an experiment which was used to calculate the wear rate for different temperatures of HT-0 to 500°C.

4. Results and Discussion

4.1. Tensile Properties. Tensile properties such as tensile strength (TS), yield strength (YS), and elongation(%) of AA6262/5456 sample are prepared by FSW procedure. Annealing or Heat treatment (HT) is carried out on a removed sample from welded plates and mechanical properties are analyzed on welded portions of AA6262/5456 plates by a variation of temperature (300–500°C) in HT process. The result of tensile properties in Figure 5 showed that the highest TS & YS (209 MPa and 178 MPa) are obtained while heating the sample at 350°C, when maintaining HT at 300°C and 500°C which leads to reduce the TS and YS values; the elongation of the joint is 11.25%, which displays 35% reduction in elongation compared with base metals, and after HT, elongation has developed expressively due to changes in HT temperature in Figure 6. The maximum elongation is obtained as16.21% at HT-500°C, followed by 15.25% at HT-300°C, 14.25% at HT-350°C, and the least elongation is observed in the welded section without the involvement of HT around 10.25%. However, TS values at various HT are almost near to base metals due to presence of molecules dispersed, steady precipitates that increasing tensile strength by restraining grain boundaries and interfering of dislocation motion [23]. The relative sliding of
ordered atomic planes occurs concurrently with plastic deformation in crystalline materials. Each atom normally moves along with the slip plane by the same integral atomic distances, but the crystal’s orientation does not change. The nearby packed planes and the highest atomic density are often the slip planes, and they considerably give to the complete extent of a tensile sample [24].

4.2. Fractured Surfaces. Analyzing fractured surfaces of tensile samples can reveal important details about the impact of the joints’ inherent microstructural characteristics on their strength and ductility [25, 26]. The fractured surfaces of the tensile test samples at different heat treatments are analyzed using SEM. The SEM photographs of three HT processes are presented in Figures 7(a)–7(c). The random adequate microscopic cracks and more voids of size variation and shape are disseminated on the fractured surface of HT-0 joint in Figure 7(a). The cracked second-phase particles and shallow dimples are found in the fracture region shown in Figure 7(b). However, the depth and width of the observed dimples are more in the fractured face of the HT-500 joint as shown in Figure 7(c). The main factor that leads to the fracture is overload, and the coalescence of microvoids controls failure. The regions near second phase particles inclusions, the structure of grain, and displacement pileups are where the voids may form. Therefore, as the strain increases during the tensile test, the microgaps expand, combine, and ultimately create a continuous fractured surface [27]. The formation of spaced β-Mg2Si particles in the HAZ at the joint might sometimes generate dimples because more severe precipitated coarsening occurred during FSW.

4.3. Wear Test. POD is a device used to execute the wear test to estimate the wear rate (WR) of welded composites at HT (0 to 500°C). Figure 8 showed the wear rate at different HT processes and noticed that WR differs from 0.0178 to 0.0258 mm³/Nm. Minimum intensity of WR was found at
HT-350°C, and maximum WR was acknowledged at HT-500°C and HT 0°C. The increments of HT (up to 350°C) reduce the wear rate value, but after above 350°C, wear rate is increasing gradually. It was discovered that the wear rate was lessened or remained constant between the heat treatment (0 to 400°C) condition. This may be connected to compensation between the softening of joints, the loss of more material, and the hardening brought on by the transformation of a soft part into hard and the precipitation of carbides. The improvement in the wear rate seen for the test piece after heat treatment under the conditions of 400 to 500°C heat treatment could be attributed to this precipitation.

4.4. Hardness Test. Hardness (BHN) of the sample across the joint varies depending on temperature variations in HT. The overall length of the sample from -20 mm to 20 mm is selected to conduct a hardness test in Figure 9. The maximum BHN (120Hv) is found at HT-300°C nugget zone distance of 0-5 mm range. The minimum value attained at HT-500°C in the distance of 10–15 mm. It is observed that the BHN value is two times more than that of base metals up to 350°C. The primary reason for this is the coarsening, dissolving, and reprecipitation of stronger precipitates brought on through the welding thermal cycle. Even though grain structure refinement might make a small benefit [2]. The loss of Guinier–Preston zones and the coarsening of strengthening precipitates, which is comparable to an over-aging process in HAZ, are responsible for the slightly decreased hardness. Due to a similar outcome of the solution treatment in TMAZ, considerable coarsening and potential

**Figure 7:** SEM image of the fractured surface at different joints. (a) HT-0 weld joint. (b) HT-350 weld joint. (c) HT-500 weld joint.

**Figure 8:** Wear test at sample heat treatment.

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full precipitate dissolution occurred. Since the material experienced higher temperature in the nugget region, some reprecipitation after full dissolving may have occurred.

4.5. Microstructure Analysis. Figure 10 illustrates the optical microscope image of base alloy AA5456 which has a homogeneous grain size of 100 μm. Figure 11 shows a microscope image of AA6262 alloy which has a considerable amount of Mg2Si particles distributed nonhomogeneously in the grain boundaries [28]. Figure 12 showed the HT-350 condition of the microstructure image at different welding zones for AA6262 plate that make up the FSW such as the stir zone (SZ), thermomechanically affected zone (TMAZ), and heat-affected zone (HAZ and noticed that the grain size of SZ is greater than TMAZ and HAZ due to the more plastic deformation and moderate frictional heat input enforced on the particular areas as a result of the tool shoulder and tool pin). Figure 13 exposed the microstructure of three weld zones for AA5456 plate after the HT-350 process and found that SZ grains exhibited are smaller than HAZ and TMAZ zones due to uniform distribution of particles by maintenance of the rotational speed of the pin.

5. Conclusion

In this work, the influence of heat treatment on the mechanical behavior for AA6262 and AA5456 joints was examined, and the conclusions are attained as follows:

1. The developments of Al composites are done by the friction stir welding process. The three considerations are selected to perform welding operation such as 1200 rpm of tool rotational speed, 25 mm/min of weld speed, and 3° of tool tilt angle.

2. The maximum tensile strength of 209 MPa was acquired when maintaining temperature (HT-350°C); similarly, supreme yield strength of the composite sample is attained at the same HT-350°C, whereas the lowest TS and YS are attained at HT-500°C and HT-300°C, respectively.

3. The maximum values of elongation are measured at HT-500°C, followed by HT-300°C (15.25%) and HT-350°C (14.25%), respectively. The welded segment without the use of HT exhibits the least elongation, which is roughly 10.25%.

4. The sample’s hardness (BHN) varies across the joint depending on temperature fluctuation in HT. At HT-300°C (nugget zone distances of 0–5 mm range), the greatest BHN (120Hv) is discovered. The lowest BHN value was obtained at HT-500°C across a distance of 10–15 mm.
(5) POD is a tool used to carry out wear tests and calculate the wear rate of welded composites at high temperatures (0 to 500°C) WR which varied from 0.0178 to 0.0258 mm3/Nm. Maximum WR is recognized at HT-0 °C & 500°C, whereas the minimum intensity of WR was discovered at HT-350°C.

Data Availability

The data used to support the findings of this study are included within the article. If further data or information are required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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