

Mechanical Properties of Corner Lap-45 Types Joined Using Friction Stir Welding

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Article history:

Received: 17 May 2024 / Received in revised form: 3 July 2024 / Accepted: 18 July 2024

Available online 21 July 2024

ABSTRACT

Solid welding has always been concerned with probe design, pins, and joint strength. Many researchers have conducted studies on joints, such as butt joints, lap joints, and T joints, but the results show low strength. This study analyzes the mechanical properties of a new design of a 90° angle joint joined by friction stir welding. This study connected aluminum 6061 using the friction stir welding method using a rectifying jig and a probe with EMS 45 material. The corner joint designs used corner-lap 45 with feed rate as independent variables in 6, 8, 10, 15, and 30 mm/min and dependent variable probe rotation speed at 1000 rpm and shoulder pressure in 584 kg. The results show low feed rates create chips and fish fins on the advancing side, and microstructure test results at low feed rates (6-15 mm/min) indicate the presence of interface bonding. The hardness value of the stir zone also shows an insignificant increase. In the tensile test results, the tensile strength decreases from the base metal value, which then the tensile strength increases along with the increase in feed rate up to a feed rate of 15 mm/min and decreases again at a feed rate of 30 mm/min.

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Keywords: Aluminum alloy 6061, corner-Lap 45, friction stir welding, jig

I. Introduction

Friction stir welding (FSW) is a solid-state joining method that involves attaching components at temperatures below melting point using heat generated by the friction of two materials [1]. This welding method was same as previous research [2]. FSW has gained considerable attention due to its potential to address many issues commonly associated with conventional welding processes. These issues include significant distortion, compaction cracking, macro and micro segregation, coarse dendritic structures, gas porosity and shrinkage, oxidation or surface discoloration, solid inclusions, the formation of brittle intermetallic compounds between dissimilar materials, extensive heat-affected zones (HAZ), environmental pollution, and high-energy consumption [3]. Because of its numerous advantages, FSW has become one of the most widely used processes for joining aluminum alloys in the industry [4].

The fundamental principles of FSW involve the friction generated by a rotating tool inserted into the interface between two workpieces, which is then moved along the welding



path. This tool typically comprises pins and shoulders. The heat generated at friction during the FSW process is generated by the tool and sheet material, resulting in plastic deformation. A fraction of the plastic deformation energy is stored within the thermo-mechanically processed region in the form of increased defect density [5]. The higher the feeding speed, the more heat is generated. This condition will greatly affect the welding results and the mechanical strength of the material [6].

Previous research indicates that controlling the process parameters—such as rotational speed, tool offset, welding speed, and tool axial force—can significantly enhance the weld quality and productivity in dissimilar friction stir welding, particularly for aluminum alloy materials [7]. Many studies have examined the quality of FSW joints on aluminum plates with butt joints [8]. However, there is little research on optimizing the feed speed on joints with a 90° angle. This research focuses on analyzing the results of macro photos, microstructures, temperature distribution, hardness values, and tensile strength values of FSW joints using the 90° angle design method with feed rate variations of 10, 15, and 30 mm/min.

II. Material and Methods

1. Materials

This experiment used aluminum 6061 (Al-Mg-Si). The sheet design is 150 mm x 100 mm and 10 mm thick, then the 150 mm long side is chamfered to form a 45° angle, as shown in Figure 1A, and Figure 1B shows the probe was made of medium carbon steel (EMS 45) was based on previously study [9].

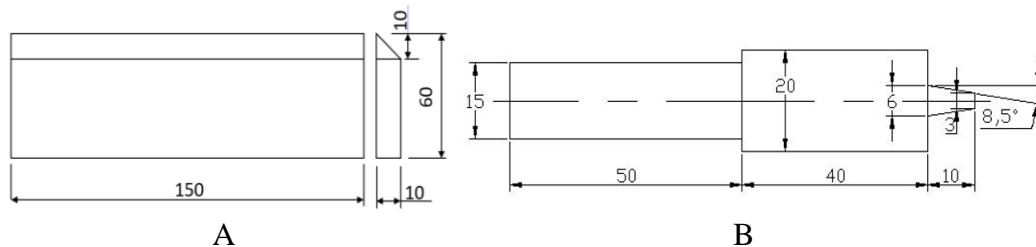


Fig. 1. Aluminum 6061 is formed to a certain size (A); Probe design in research (B)

2. Welding Process

Jig holes are made with a diameter of 7 mm, at a wide distance of 20 mm and a depth of 20 mm to install thermocouple, as shown in Figure 2A. The Probe (Figure 2B) was rotated at 1000 rpm with feed rate of 6, 8, 10, 15, and 30 mm/min. and shoulder pressure of 584 kg.

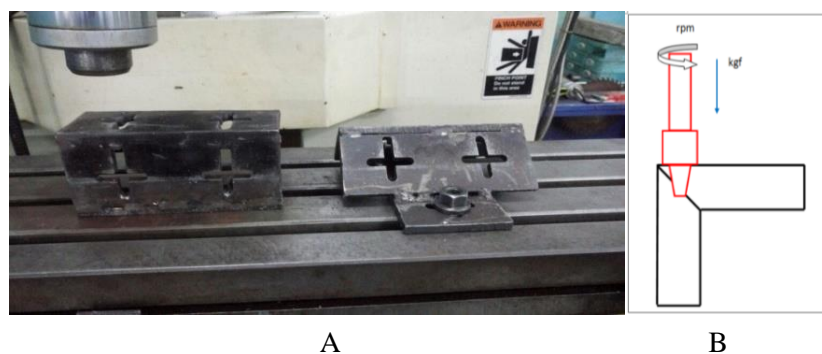


Fig. 2. Jig design (A); Joints corner-lap joint with a 90° angle design (B)

3. Temperature Analysis

The heat input must be considered to obtain a high joining strength in the process. Heat input was measured using a thermocouple. The temperature profile was analyzed to assess its impact on the development of microstructure and the strength of FSW joints in corner-lap joints 45. Additionally, the temperature distribution for the subsequent process should also be examined.

4. Microhardness Analysis

Microhardness Vickers was measured at the FSW joints Corner-Lap 45 along a line. Microhardness was determined by applying a load of 500 g for 10 seconds at a distance of 500 μm among indentations. Ten indentations were made on the same surface side of each variation at various places, with a minimum interval of 1 mm between any two indentations.

5. Microstructure Analysis

Microstructure analysis was used to evaluate the phase after the FSW method. Microstructure photo observed under a metallurgical microscope with a magnification of 100 times to identify the resulting steel phase and compare the weld, thermomechanically affected zone (TMAZ), and HAZ area.

6. Tensile Strength Analysis

Loading on the tensile test machine was done in the opposite direction of the interface plane, as shown in Figure 3. The shear and cross-tension tests were performed in line with ISO 14273. The tests were performed on a universal testing machine weighing 2000 kg and with a set cross-head speed of 10 mm/min. With the joint forming a 90° angle and a slope of 45°, the force description must be calculated. The tensile test force analysis of a Corner-Lap 45 joint force is broken down into horizontal and tangential forces. The tensile force is divided by the area of the weld fracture.

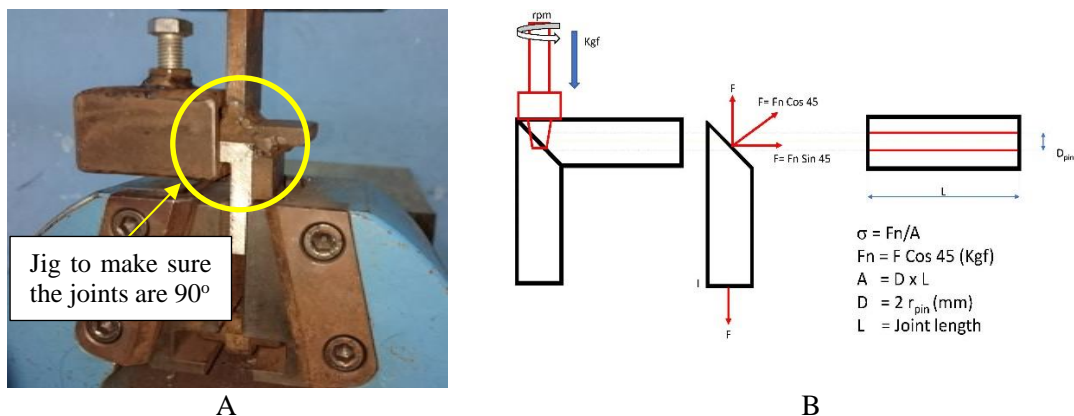


Fig. 3. Tensile test jig design (A) and Tensile test method and direction of force (B)

7. Macro Photo Analysis

The macro photo was used to describe how FSW affects the deformation and shape change of the joints. The photo was taken with a DSLR camera with a macro lens to show heat maps and plot figures to highlight the areas with defects, especially in the process joint area.

III. Results and Discussions

1. Temperature Analysis

Simulation of the distribution and measurement results of the heat value generated from the FSW process is shown in Figure 4 and Figure 5. Figure 4B shows the heat distribution at high feed rates. Figure 4C is centered and controlled near the rotating probe. At low feed rates (Figure 4D), the heat distribution propagates widely on the entire workpiece.

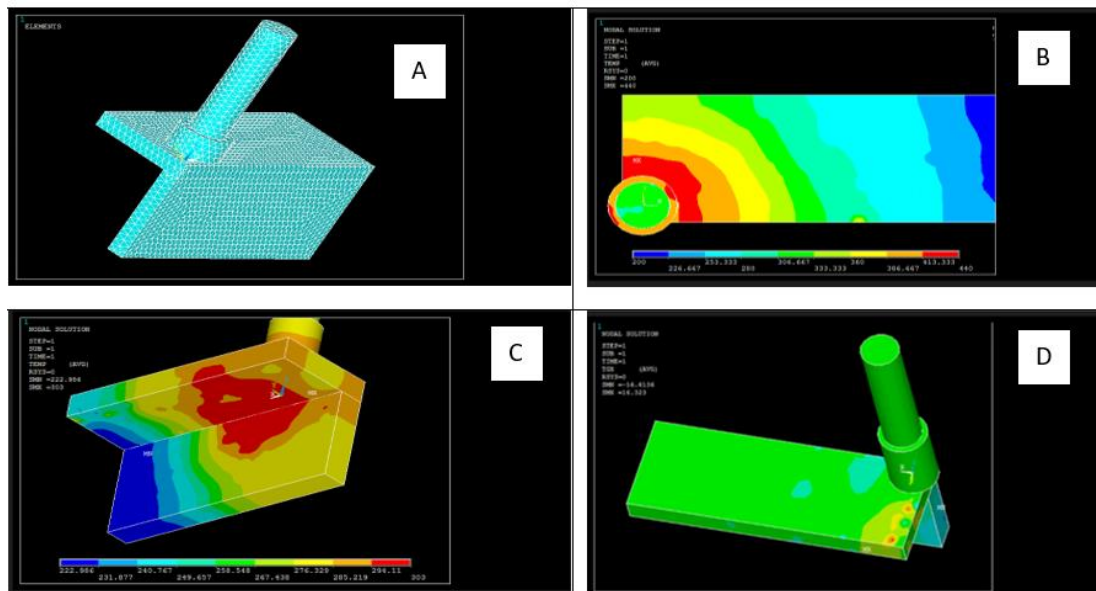


Fig. 4. (A) Meshing, (B) Temperature distribution 15 min., (C) 8 min., (D) 4 min.

The heat input must be considered to obtain a high joining strength in the process because the heat during friction welding that combined effect of frictional and physical heating due to the plasticity of the stirred material [10]. Figure 5 shows the faster the feed rate of the FSW probe, the lower the temperature generated. This is in accordance with the simulation results shown in Figure 4, where the heat center generated is more focused, and there is no longer preheated process on other parts of the workpiece. The heat generated in the FSW process can affect the mechanical strength and microstructure of the joint, which can change the properties of a material [11]-[13].

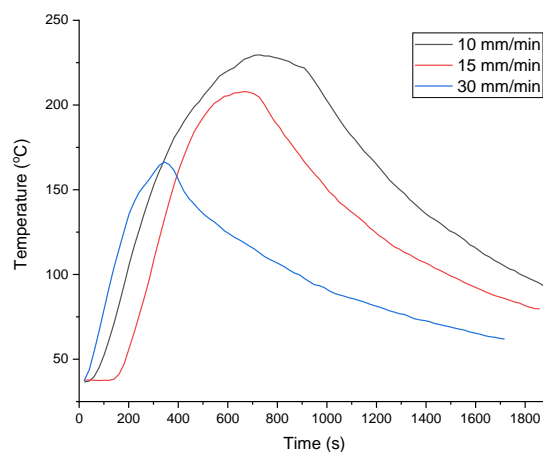


Fig. 5. Temperature distribution at corner-lap joint 45

2. Microhardness Analysis

The hardness of the joint was assessed using the Vickers microhardness method at the intersection point of the weld joint at a 45° angle, with the results presented in Figure 6. Measurements were taken along one line at a 45° angle to the FSW joint. The findings indicate that the Stir Zone (SZ) exhibits increased hardness. This enhancement in hardness is attributed to the finer grain size in the SZ compared to the Base Metal (BM), as previously discussed in the metallographic section.

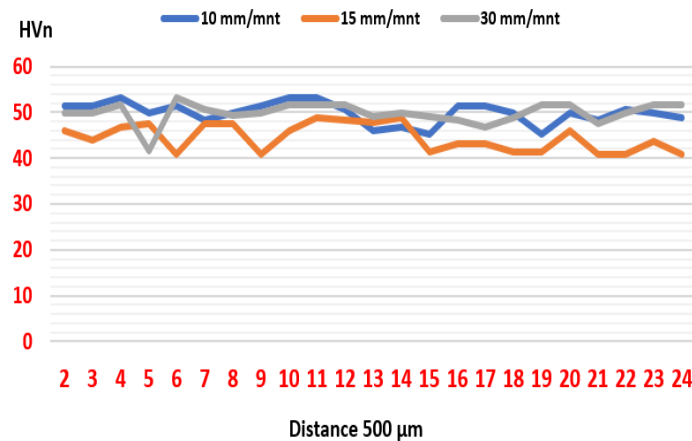


Fig. 6. Vickers microhardness of corner-lap joints 45

Vickers microhardness measurements were conducted along a line at the corner-butt 45° of the FSW joints. The results demonstrate an increase in hardness in the SZ. This increase is due to the SZ's finer grain size compared to the BM, as noted in the metallographic section. Since grain boundaries are a primary factor in dislocation slip, smaller grain sizes exhibit higher resistance to local plastic deformation, leading to greater strength and hardness during the microhardness test indenter's penetration [14]. Increment in the grain size has been observed with increasing rotational speed, whereas it was found to decrease with increment in the number of passes [15]. Three different shoulder profiles were tested, and it was found that the concave profile shoulder with a scroll feature on the bottom surface significantly improved the welding joint properties and reduced undercut defects [16]. TMAZ hardness is higher than the nugget zone and higher than HAZ. At the weld line, the hardness decreases from BM of 190 HV to a minimum located in the HAZ, then increases to a maximum in SZ, but lower than the hardness of BM caused by softening in SZ is caused by solution deposition. Maximum hardness occurs in SZ due to natural fine aging and recrystallization of 155 HV, which is about 80% of BM [17].

3. Microstructure Analysis

Microstructure analysis was employed to evaluate the phases resulting from the FSW method. All joints exhibited three distinct zones: the heat-affected zone (HAZ), the thermo-mechanically affected zone (TMAZ), and the weld nugget zone (WNZ). In the WNZ, the spin pattern structure of the probe is clearly visible, with the upper part mainly influenced by the upper shoulder. The microstructure, as shown in Figure 7, prominently features the interface bonding. The interface between the recrystallized WNZ and the parent metal is relatively diffuse on the retreating side of the FSW tool but quite sharp on the advancing side (AS), consistent with findings from previous studies [12], [13]. This interfacial bond is a form of Al₂O₃ oxide layer that is not stirred much by the pin and is dependent on feed rate;

when the heat input is low, then low heat energy is produced, causing low plastic material flow. The plastic material forms zig-zag black spots along the layer lines and makes interface bonding, as shown in Fig. 7.

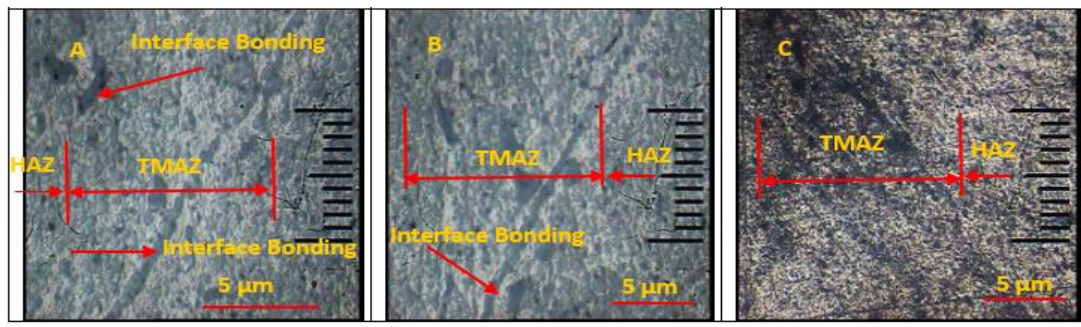


Fig. 7. Microstructure at 200 x magnification of corner-lap 45 (C-L 45) with the feed rate of A) 10 mm/min, B) 15 mm/min, C) 30 mm/min.

Figure 7 shows the SZ microstructure corresponding to the feed rate variation. The lower the feed rate, the higher the frictional heating/heat input per unit length, which affects the microstructure of the workpiece and causes grain growth [18]. This is attributed to welding with a low feed rate, where the specimen is exposed to frictional heating for a longer duration compared to welding with a high feed rate. A previous study reported similar findings, suggesting that at this feed rate, once the maximum temperature is reached, static grain growth may occur following recrystallization [19].

4. Tensile Strength Analysis

The results of the tensile welding test, as shown in Figure 8, indicate that a feed rate of 10 mm/min results in a tensile strength of 64.9 MPa, while a feed rate of 15 mm/min achieves the highest tensile strength of 119 MPa. At a feed rate of 30 mm/min, the tensile strength decreases to 62 MPa. These findings suggest that friction stir welding offers an effective method for joining aluminum, combining satisfactory results with faster and stronger performance. The minimal variation in ultimate tensile strength (UTS) across the welds implies that a change in tool rotational speed of 300 rpm may not significantly affect the UTS of the weld [6].

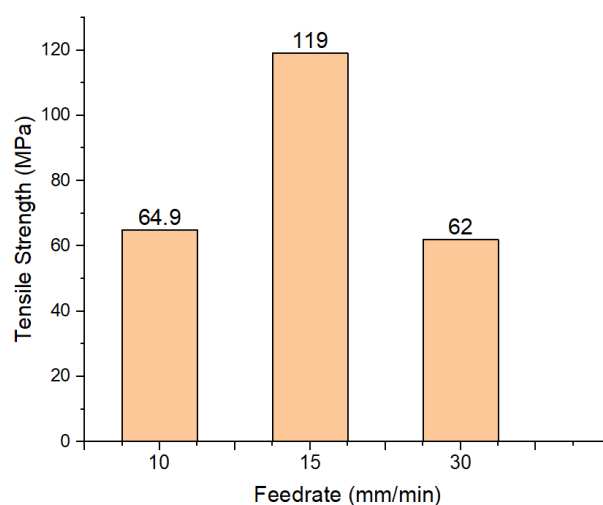


Fig. 8. Tensile strength comparison for corner-lap joints 45 joints

During the welding process, high-strain-rate deformation and elevated temperatures can induce substantial microstructural changes that influence mechanical properties. Dynamic Recrystallization (DRX) grains formed in the SZ lead to notable material softening in this region. This phenomenon is attributed to the reduction of work-hardening effects due to DRX during FSW. Consequently, the relatively low UTS and yield strength (YS) of the joint are primarily due to the decreased dislocation density in the weld zone. As a result, all the joints show a significant reduction in YS and UTS compared to the BM [18].

5. Macro Photo Analysis

Figure 9 depicts a macro photo of the path of the welding joint. All samples in Figure 9 show that FSW produces fin-shaped chips on the top layer of aluminum that wriggle and form along the surface of the probe trajectory, especially the advancing side.

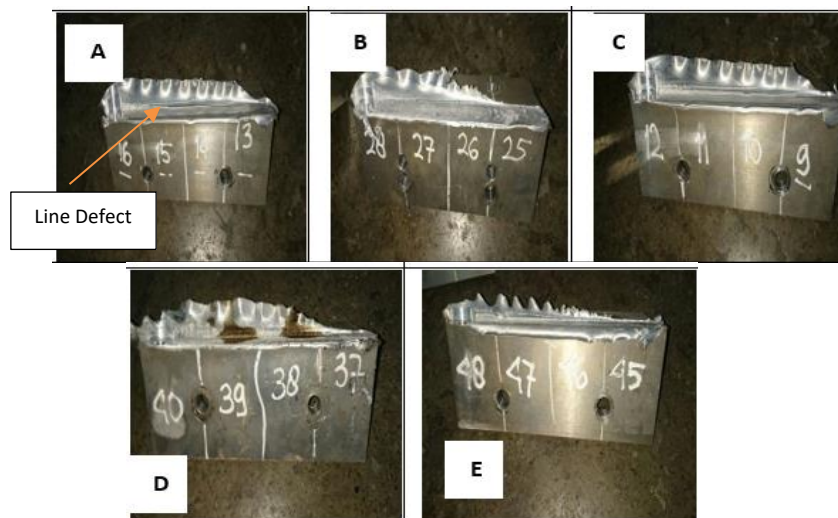


Fig. 9. Macro photo results of corner-lap 45 connection (C-L 45) in the feed rate of (A) 6 mm/min, (B) 8 mm/min, (C) 10 mm/min, (D) 15 mm/min, and (E) 30 mm/min

Figure 9A and Figure 9B show that many nuggets or chips have formed from the surface of the probe, especially the shoulder, which is unable to hold the plastic material. This is largely influenced by the convex shape of the shoulder so that it is unable to hold nuggets or chips as filler metal and also high temperature above 400°C, which occurs at $v=8$ mm/min and a probe pressing force of 584 kg. Figure 9C experiments (No. 9, 10, 11, and 12) at $v=10$ mm/min, probe pressure 584 kg, and temperatures reached above 400°C resulted in many nuggets or chips coming out and long line defects appearing, this can occur because the sliding speed is slightly higher, there is an effect of cutting the shape of the line by the pin. Figure 9D and 9E will show the same thing so that a low Tensile strength will be obtained and the texture formed is also the same. The convex shape of the shoulder influences this, and the force applied so that it cannot hold the chip to exit through the advancing side. The fins formed on the advancing side are also affected by the high temperature above 400°C caused by the friction of the probe and the workpiece [20], [21].

At a probe rotation speed of 1000 rpm with a low feed rate, the resulting fins become more frequent because the heat generated becomes excessive and makes the metal in the TMAZ part come out [22]. While at high feed rates, the fins produced become less because the stirring process in each section takes place faster and makes the melted metal in the TMAZ section not have time to get out of the track [23].

IV. Conclusions

Based on the results of this study, low feed rates create chips and fins on the advancing side of the welding line which as the feed rate speed increases, fewer chips and fins are formed. The heat caused by too low feed rate causes a change in the character of the FSW connection with BM, where the microstructure test results at low feed rates (6-15 mm/min.) show the presence of interface bonding, while at a feed rate of 30 mm/min. interface bonding is not formed. The hardness value of SZ also shows an insignificant increase, where the increase tends to fluctuate depending on the feed rate used. In the tensile test results, the mechanical strength value shows a decrease from the BM value, and then the tensile strength increases with the increase in feed rate up to a feed rate of 15mm/min. and decreases again at a feed rate of 30 mm/min.

Acknowledgment

This research was funded by Damas Vocational School, Gadjah Mada University. Thank you to the Mechanical Engineering Department for providing laboratory facilities.

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