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THE EFFECT OF FRICTION SPOT STIR WELDING IN INSTALLING DOUBLE COVER RIVET LAP JOINTS ON ALUMINUM 2024 – T3 AND 7075 – T6 WITH MECHANICAL STRENGTH

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Abstract

Selection and treatment of materials in the aerospace, marine, transportation, and manufacturing industries are crucial for achieving efficient configurations. Aluminum is one of the materials widely used in these industries due to its lightweight, corrosion resistance, and good electrical conductivity properties. Aluminum alloys 2024-T3 and 7075 are often used in aircraft component manufacturing due to their strength and excellent corrosion resistance. The commonly used joining method is riveting, but there are also other methods such as friction spot stir welding (FSSW). In this study, joining was performed using rivets and followed by the FSSW process on aluminum plates of types 2024 and 7075. The objective of this research is to investigate the mechanical strength of rivet joints combined with the FSSW process on plates with different types. A literature review on aluminum, alloys 2024-T3 and 7075-T6, as well as the riveting and FSSW joining methods, was also conducted. The experimental method involved joining the two types of plates using rivets and subsequently performing the FSSW process. The results of this research are expected to provide a better understanding of the mechanical strength of rivet and FSSW joints on aluminum plates with different types.

***Keywords**: Mechanical Properties, Alloy 2024-T3, Alloy 7075-T6, Rivet, Friction Spot Stir Welding (FSSW).*

1. INTRODUCTION

The selection and treatment of a material is very important. Especially the progress and technology in the aerospace, marine, transportation and manufacturing industries [1, 2]. The selection of materials is adjusted to the purpose of making a component, so that it can create a good and efficient configuration One of the materials widely used in the industrial world is aluminum, the second row of certain chapters/sub-chapters. Aluminum is a light metal and has good corrosion resistance, good electrical conductivity and other properties.

The AA2024 T3 and AA7075 T6 series are widely used in aerospace structures due to their high strength-to-mass ratio, but are susceptible to softening of precipitates in the HAZ during the fusion process [3]. Solid state approaches such as FSSW reduce peak heat input and prevent solidification cracks, making them more suitable for thin-layered skin panels and substructures. The aluminum alloy widely used in engineering is the 2024-T3 series aluminum alloy, which is an Al-Cu metal alloy with copper

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ranging from 3.8–4.9%, while T3 is a heat treatment process consisting of solid solution, quenching, and aging to achieve a better hardness level [4].

In addition, aluminum alloy 7075 T6 is also widely used in the aircraft industry for components in spars, stabilizers, frames that require high strength and low density The characteristics of aluminum alloy 7075 T6 have good corrosion resistance properties [5]. Thus, aluminum can be a constituent material in certain components that interact a lot with water and air. The use of aluminum that is easy to manufacture is usually done by connecting using rivets.

Industrial needs are shifting from conventional rivets to hybrid joints, which are easier and have mechanical advantages with metallurgical bonds. In aircraft components, especially in the skin section, many use rivets as a joining method [6]. Rivet installation uses a rivet gun with a certain calculated pressure, so as not to damage the skin surface. However, there are other methods that can be used besides rivets, namely friction spot stir welding. Friction spot stir welding is a welding method that utilizes the friction force of the tool pin on the material and without the use of filler metal [7, 8]. In this study, the focus is on joining two types of materials, aluminum 2024 and 7075 T6, using rivets and the FSSW method. The FSSW process is often used on aluminum alloys, especially in the automotive and aerospace industries, as an alternative to resistance spot welding [9]. The purpose of this study is to evaluate the strength and hardness of rivet joints combined with the FSSW method on aluminum plates of different types. This method is commonly used in the aerospace, marine, transportation, and manufacturing industries. This research is crucial for understanding joint quality in practical applications and industrial technology development. The FSSW process can improve shear and fatigue capacity without adding excess mass.

2. METHODS AND MATERIALS

2.1. Research Design or Plan

The research was conducted experimentally by creating specimens that would undergo mechanical testing using shear and hardness tests, as well as microscopic testing using macro and micro tests. The specimens in this study were two plates of different types, namely 7075 aluminum plate and 2024 aluminum plate. The plates would be connected using a lap joint configuration using double rivets. After the connection process was completed, FSSW was performed on each rivet and then the specimens were tested according to the research flowchart in Fig 1.

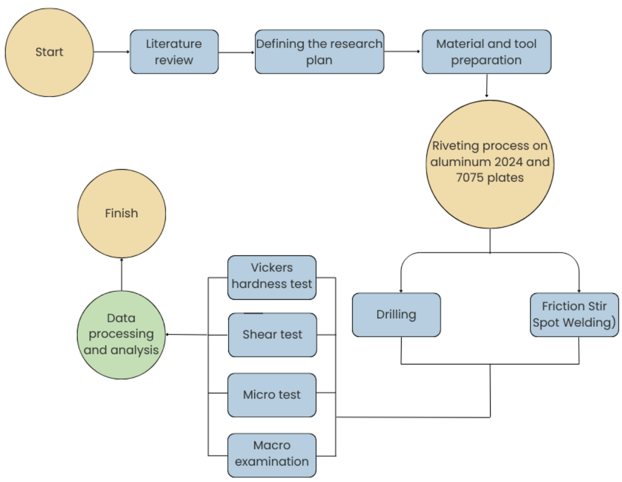

Fig 1. Research flow diagram

Data from the results of shear and hardness tests are in quantitative and graphical form, while data from the results of microscopic tests are in visual or image form. In conducting the research, Fig 2. (a) is the plate dimension and FSSW distance used to carry out the spot welding process, Fig 2. (b) is a rivet installation scheme after the FSSW process and Fig 2. (c) is the tool shoulder dimension used in carrying out the FSSW process.

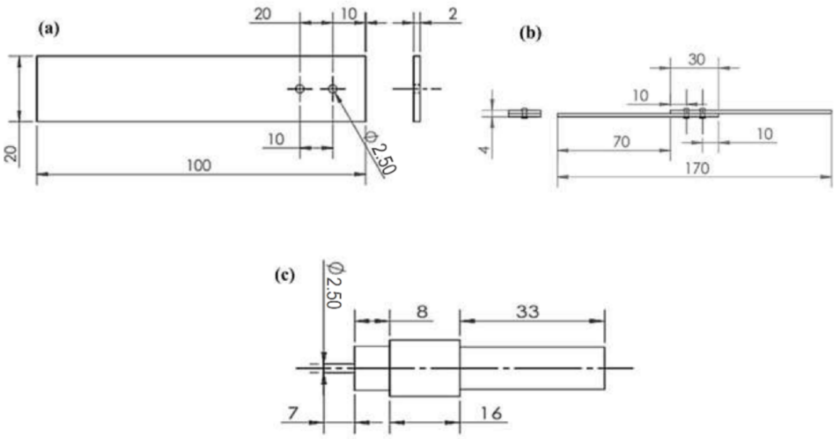

Fig 2. (a) Plate dimensions and FSSW distance, (b) Rivet installation scheme, (c) FSSW tool.

The material joining process in this study was carried out using a conventional milling machine that has been specially modified into a Friction Stir Welding (FSW) device. This modification allows the machine to function as the main instrument in the solid-state welding process, where the joint is formed through mechanical friction without passing the melting point of the material. The entire series of welding experiments were carried out at the Production Laboratory, Yogyakarta Aerospace Technology College (STTKD), by utilizing a milling-drilling machine unit as the main tool driver. In its implementation, the welding process was controlled using precise technical parameters to ensure optimal joint quality. The parameters applied included a tool rotational speed (spindle speed) of 2200 rpm and a welding speed (traverse speed) of 30 mm/min. In addition, the tool position was set at a tilt angle of 0^o to the vertical axis (perpendicular to the x-axis on the workpiece) to maintain the stability of heat distribution during the joining process.

2.2. Specimen Testing

A series of mechanical and metallurgical tests were systematically conducted on the specimens to evaluate the joint characteristics. The first test was a tensile-shear test using a universal tensile testing machine. In this procedure, both ends of the specimen were clamped in the machine's grips, with the lower end held static while the upper end was pulled axially until the riveted joint failed (fractured). The maximum shear load data was recorded in real time via a computer-integrated data acquisition system for further analysis.

After the mechanical tests were completed, a structural evaluation was conducted at the fracture site, specifically for the FSSW (Friction Stir Spot Welding) joint. This process began with macroscopic examination to visually identify the failure pattern. Next, the specimens were sectioned cross-sectionally at the joint site for hardness testing and microscopic examination.

For metallographic purposes, the specimens were mounted using resin, followed by grinding and polishing to achieve a mirror finish. The test specimens in this study used a single lap joint configuration with double rivets. The type of rivet used was aviation standard MS20470, chosen to suit the characteristics of the aluminum material used.

2.3. Aluminum 2024-T3

The 2024 series aluminum alloy is a material that is widely implemented in the aerospace industry, especially as a major structural component such as aircraft skin. This material belongs to the aluminum-copper alloy (Al-Cu alloy) group with the main alloying element composition consisting of 4.4% Copper (Cu), 1.5% Magnesium (Mg), and 0.6% Manganese (Mn). The superior mechanical characteristics of this series are achieved through precipitation strengthening or heat treatment mechanisms, specifically identified by the temper suffix "T" (e.g. T3). The combination of chemical elements and thermal treatment produces a material with a high strength-to-weight ratio and excellent fatigue resistance, making it the gold standard in aircraft manufacturing applications [9] .

2.4. Aluminum 7075-T6

Aluminum 7075-T6 is a high-strength aluminum alloy variant widely applied in the aerospace, defense, and high-performance automotive industries. The main characteristic of this series is its ability to improve its mechanical properties through special heat treatments, where the T6 temper indicates that the material has undergone an artificial aging process to achieve maximum strength [10]. This alloy offers a superior combination of high mechanical strength, low density, and an optimal strength-to-weight ratio. Metallurgically, Aluminum 7075-T6 is dominated by the main alloying elements of Zinc (Zn) at 5.4%, Magnesium (Mg) 2.4%, and Copper (Cu) 0.14%, with a pure aluminum composition of around 92% [11]. The presence of MgZn_2 phase precipitates formed from zinc and magnesium alloys contributes significantly to the material's resistance to high stress loads. Apart from the strength aspect, this material is also known to have good fracture toughness and damage tolerance, making it an ideal choice for critical structural components [12].

2.5. Rivet

The joint construction in this study uses MS20470 (Universal Head) type rivets, which are widely implemented in aerospace structures due to their superior mechanical characteristics. The joint configuration is designed in the form of a single overlap joint with double rows of rivets (Single Lap Joint, Double Riveted), as illustrated in detail in Figure 5. The selection of this configuration aims to evaluate the load distribution and shear strength in the overlap area between the 2024 and 7075 aluminum plates.

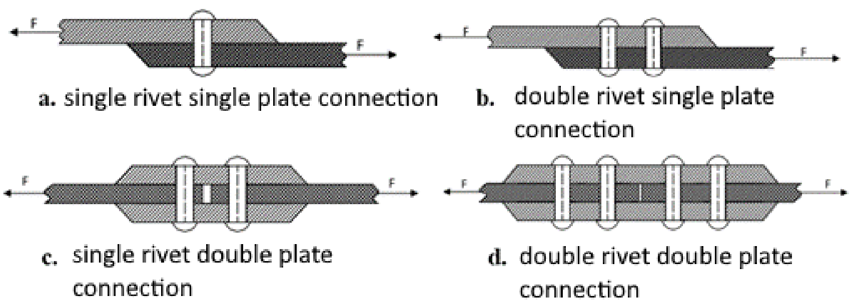

Fig 5. Configuration of installing rivets on the plate

2.6. Friction Spot Stir Welding

Friction Stir Spot Welding (FSSW) is a joining method developed from the Friction Stir Welding (FSW) technique. The basic mechanism of FSSW involves the use of a rotating tool consisting of a shoulder and a pin that penetrates the surface of the plates to be joined. Unlike conventional welding, this process does not require additional filler metal. The heat generated from friction between the tool and the workpiece causes the material to soften until it reaches a plastic state. After the tool is retracted, the plastically deformed material fuses and resolidifies, creating a strong interfacial bond.

Fundamentally, FSW and FSSW are similar in that they utilize frictional heat to reach the material's plastic point [13]. However, the main difference between the two lies in the tool's kinematic path during the stirring process. In FSSW, the tool only performs penetration and compression movements at a single location without any transverse or longitudinal motion. The term "spot" in this method refers to the localization of the joint that forms only at a specific point, making it an efficient alternative to riveting or resistance spot welding on thin-plate structures. A detailed schematic of the FSSW process steps is shown in Fig 6.

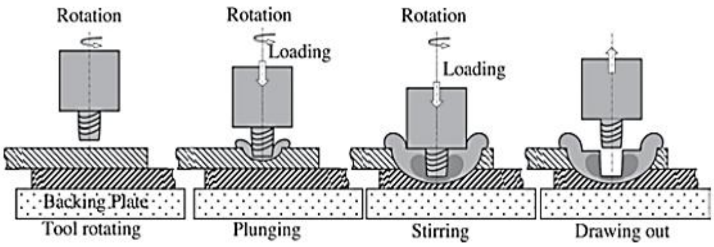

Fig 6. FSSW process schematic

Shear Test

Shear testing is conducted to evaluate the mechanical characteristics and integration strength of material joints. In principle, this test utilizes a tensile testing machine, but the applied tensile load acts parallel to the joint interface, resulting in shear stress in the specimen. Through this procedure, the material's response to external loads can be specifically observed, particularly in determining the maximum load the joint can withstand before failure [14].

In this study, the specimens tested were lap joints resulting from welding or mechanical joining. The tensile load was applied perpendicular to the joint cross-section to induce pure shear forces in the nugget or rivet area. A schematic illustration of this shear test configuration is presented in detail in Figure 7.

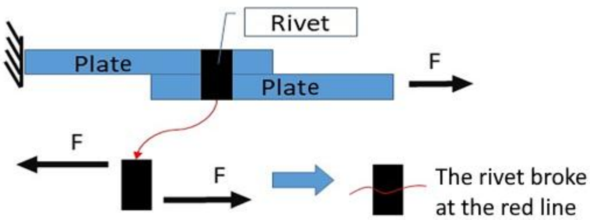

Fig 7. Illustration of shear test

Based on the visualization in Fig 7, the determination of the critical cross-sectional area in stress calculations is based on the cross-sectional area of the rivet shank that receives the shear load directly. Under transverse loading conditions, mechanical failure generally occurs due to shear forces acting perpendicular to the longitudinal axis of the rivet. Therefore, the magnitude of the average shear stress (σ) that occurs in the connection can be calculated using Equation 1 as follows:

$$\sigma = \frac{F}{A} \quad (1)$$

Where:

σ = Shear stress (MPa)
F = Load or shear force acting on the rivet (N)
A = Cross-sectional area of the rivet shank (mm^2)

The mechanical characteristics of the joined material were evaluated through a series of shear tests to determine its strength and deformation behavior. The analyzed mechanical parameters were derived comprehensively from the stress-strain curve, as represented in Figure 8. Through this curve, several crucial material phenomena can be identified, including the yield point which marks the beginning of plastic deformation, the maximum shear stress (ultimate shear strength), and the level of ductility of the material before experiencing fracture failure. This analysis is very important to understand the structural integrity of the joints in 2024 and 7075 aluminum plates due to the influence of welding parameters.

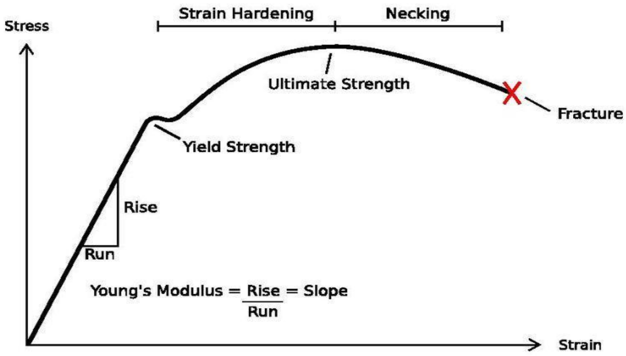

Fig 8. Stress-strain curve

2.7. Hardness Test

Hardness testing is a destructive mechanical testing method in which the specimen surface is penetrated by an indenter with a specific load, forming a permanent deformation trace. According to [15], based on the geometry of the indenter used, hardness testing is classified into three main methods: the Ball Indentation Test (Brinell), the Cone Indentation Test (Rockwell), and the Pyramid Indentation Test (Vickers).

In this study, the Vickers Hardness Test was chosen. This method was chosen based on the relatively small dimensions of the research specimens and the need for high accuracy in micro-areas. The diamond pyramid indenter in the Vickers test allows for measurements in a narrow area with a very small but still representative indentation trace. Based on the standards referenced in [16] the Vickers hardness value (VHN) is calculated based on the ratio of the compressive load to the surface area of the indentation trace, which is mathematically expressed in Equation (2):

$$VHN = \frac{1{,}8544xP}{d^2} \quad (2)$$

Where:

VHN = Vickers hardness number (HV)

P = Load (kgf)

d = Diagonal width of the indenter (mm)

2.8. Metallographic Test

Metallographic examination is performed as a visual evaluation method to analyze material structure at a microscopic scale. This testing serves as a complementary analysis to mechanical testing, identifying specific metallurgical phenomena that occur during the joining process. In the context of Friction Stir Spot Welding (FSSW) research, observations focus on the structural integrity of the joint area (nugget zone) to detect the presence of weld defects such as voids, tunneling, and hooking, which can affect the material's mechanical strength.

Furthermore, this characterization aims to map microstructural changes in various heat-affected zones, including the Stir Zone (SZ), Thermo-Mechanically Affected Zone (TMAZ), and Heat Affected Zone (HAZ). Through these observations, the correlation between welding parameters such as tool rotational speed and pressure time-and the crystal grain distribution and interfacial bond quality between 2024 and 7075 aluminum plates can be comprehensively analyzed.

3. RESULTS AND DISCUSSION

3.1. Shear Test

The increasing demand for lightweight structural materials in the aerospace industry has driven the development of innovative joining techniques capable of achieving high mechanical strength without significantly increasing mass. AA2024-T3 and AA7075 aluminum alloys are standard materials widely used in aircraft structural components due to their superior strength-to-weight ratio.

In this study, the mechanical strength of riveted joints prepared using two different drilling methods was evaluated: conventional drilling and friction stir spot welding (FSSW), which serves as both the drilling and initial joining technique. Lap shear test specimens were prepared using 2024 and 7075 series aluminum plates to determine the maximum load capacity and shear stress that the joints can withstand. The specimen technical data and the results of the maximum point load and shear stress tests are summarized in Table 1.

Tabel 1. Rivet Connection Tensile Shear Test Results

Method	No	Diameter (mm)	Sectional Area (mm^2)	Maximum point load (N)	Shers Stress (Mpa)
Drill	1	2.5	4.91	3569.42	727.53
	2	2.5	4.91	2962.88	603.90
	3	2.5	4.91	2894.53	589.97
		Average			**640.46**
FSSW	1	2.5	4.91	3488.62	711.06
	2	2.5	4.91	3117.34	635.38
	3	2.5	4.91	3873.25	789.45
		Average			**711.96**

Test results show that the Friction Stir Spot Welding method has superior mechanical performance compared to conventional (drill-rivet) joining methods. The average shear stress value produced by the FSSW method reached 711.96 MPa, while the drilling method only achieved 640.46 MPa. This increase in strength indicates that the FSSW joint is capable of withstanding a greater maximum shear load at identical specimen dimensions and test parameters.

This phenomenon aligns with a literature study on Aluminum 2024-T3 riveted joints, which found that FSSW can increase shear strength by up to 33% compared to the drilling method [17]. This performance improvement is driven by grain refinement and increased hardness in the Heat Affected Zone (HAZ) as a result of heat distribution and plastic deformation during the FSSW process. Conventional drilling joining methods have inherent weaknesses, including increased stress concentration and the risk of crack initiation in the rivet hole. As an alternative, Friction Stir Spot Welding technology offers an innovative solid-state joining process that utilizes frictional heat. This method can produce a more homogeneous metallurgical bond, minimize thermal distortion, and reduce structural defects commonly found in conventional mechanical joints.

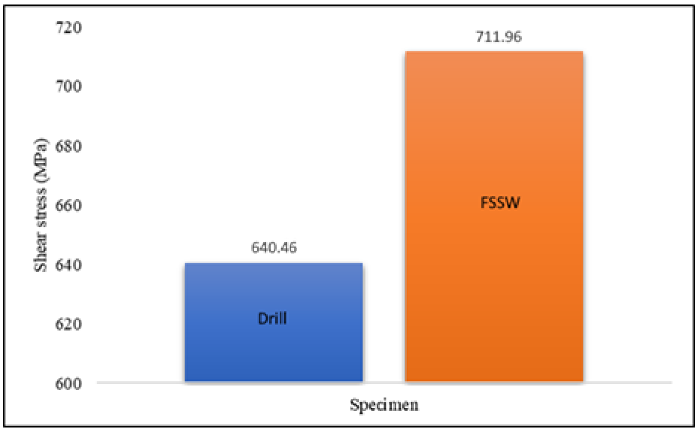

Fig 9. Comparative analysis of shear stress between conventional drilling-riveting and Friction Stir Spot Welding (FSSW) connection methods.

3.2. Hardness Characteristics of FSSW and Rivet Joints on Double Cover Lap Joint Al 2024-T3/7075.

Friction Stir Spot Welding (FSSW) is a solid-state joining method capable of engineering grain refinement at the joint, potentially improving the mechanical properties and hardness distribution of the material. This study aims to analyze the effect of FSSW parameters on the hardness profile of a double-cover lap joint configuration made from 2024-T3 and 7075 aluminum, by comparing it to conventional riveting (drilling) joining methods.

Based on macrostructural observations in Fig 11, several critical zones formed by heat input and plastic deformation were identified. These zones include the Heat Affected Zone (HAZ), an area that experiences microstructural changes due to thermal cycling without direct mechanical deformation. Furthermore, observations focused on the Upper Plate (Upper Plate), Lower Plate (Down), and the transition area of the rivet.

Localized hardness testing was conducted using the Vickers Hardness Test to map variations in hardness values at specific points within each zone. This aimed to evaluate the thermomechanical impact of the FSSW process compared to the purely mechanical effects of the drilling method. Comprehensive data regarding the distribution of hardness values are presented in detail in Table 2.

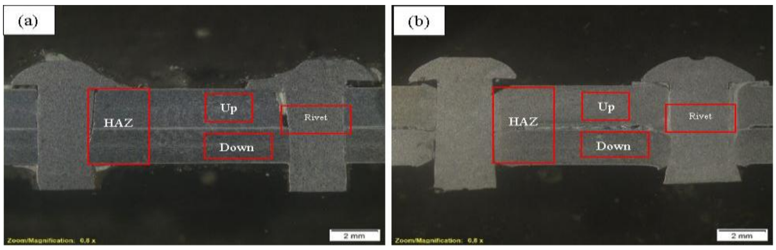

Fig 11. Macro structure of cross-section of the joint: (a) Drill method, (b) FSSW method.

Table 2. Micro Vickers hardness test results data on FSSW joints.

Variations	Specimens	d1	d2	d (μm)	d (mm)	VHN (μm/g)
DRILL	RAW	35	37	36	0.0360	143.06
	HAZ	37	38.5	37.75	0.0378	130.10
	RIVET	38.5	42	40.25	0.0403	114.44
FSSW	RAW	38	40	39	0.039	121.89
	HAZ	38.5	40	39.25	0.0393	120.35
	RIVET	36.5	38	37.25	0.0373	133.62

The hardness test results for the drilling method showed the highest value of 143.06 VHN (specimen 1) and the lowest of 114.44 VHN (specimen 3). The decrease in hardness in the Heat Affected Zone (HAZ) is caused by heat from the friction of the drill bit, which changes the material's microstructure. Conversely, in the Friction Stir Spot Welding (FSSW) specimens, hardness degradation in the joint area and HAZ was much more significant than in the base metal. This occurs because the thermal cycle in FSSW reaches higher temperatures and lasts longer than in the drilling process. This high heat input triggers annealing and grain growth in the aluminum alloy, resulting in lower overall hardness values from FSSW [18].

Test results show significant differences in hardness characteristics between the Friction Stir Spot Welding (FSSW) method and conventional drilling. In the FSSW process, the longer interaction between the probe and the workpiece results in higher heat input than in the drilling process. This thermal phenomenon triggers dynamic recrystallization in the stir zone, resulting in a finer grain structure (grain refinement) in accordance with the Hall-Petch law. Conversely, the drilling method tends to cause greater grain growth around the rivet hole due to mechanical deformation without adequate thermal control, significantly reducing local hardness. Although the high temperatures of FSSW can cause softening in the heat-affected zone, the plasticization and grain size reduction process at the joint point results in a more stable microstructure and superior local hardness compared to the conventional drilling method.

3.3. Macrostructural and Microstructural Analysis

3.3.1. Macro-structural comparison of Al 2024

The macrostructural observations in Fig 12 reveal that FSSW induces more pronounced plastic deformation in the rivet hole area compared to the drilling method. This deformation correlates with the mechanical testing results, where the drilling method exhibits higher hardness and shear strength. These findings suggest that the thermal cycle during the FSSW process leads to localized softening, thereby reducing the overall joint integrity of the AA2024 alloy.

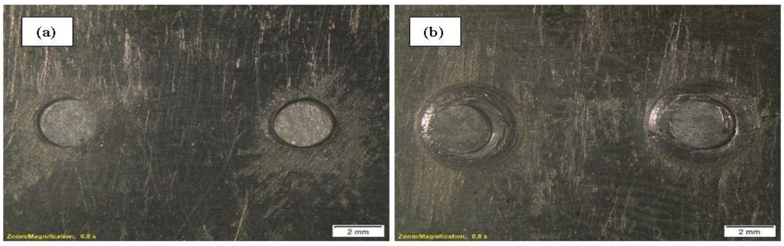

Fig 12. Macro-structural analysis of FSSW joints on AA2024

Fig 13 illustrates the macrostructural results of the Al 7075 alloy. The FSSW process exhibits more pronounced plastic deformation in the rivet hole area compared to the drilling method. This structural behavior aligns with the mechanical testing data obtained in this study.

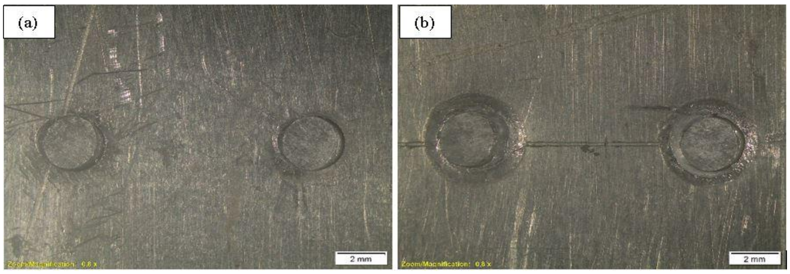

Fig 13. Macrostructural observation of Al 7075 specimens

3.3.2. Microstructure Observation

Fig 14 and 15 present a comparison of the microstructure between the base metal and the Heat Affected Zone (HAZ). Observations indicate changes in grain morphology, where the microstructure elongates compared to its initial state. This phenomenon is triggered by heat input resulting from friction between the probe or drill bit and the aluminum plate. The increase in thermal energy due to tool rotation has been shown to significantly affect grain size. Consistent with findings [19] moderate heat increases can trigger microstructural size reduction through recrystallization. Furthermore, [20] explains that areas experiencing direct contact and friction with the tool will exhibit a finer grain structure (grain refinement) due to intense plastic deformation during the welding process.

Drill

FSSW

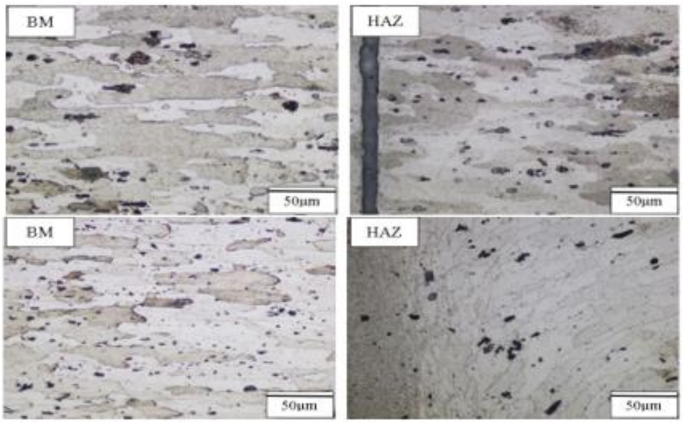

Fig 14. Microstructure of AA 2024

Drill

FSSW

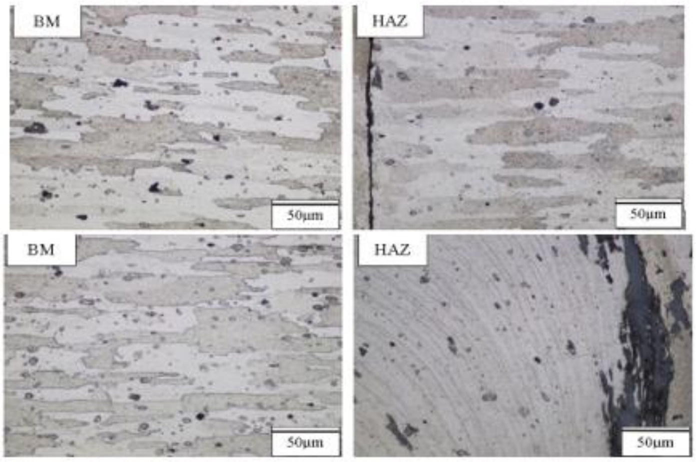

Fig 15. Microstructure of AA 7075

Microstructure observations in AA 2024 and AA 7075 show significant grain transformation between the base metal (BM) and the Heat Affected Zone (HAZ). In the BM area, the grain structure shows initial working characteristics that tend to be uniform. However, after the joining process, grain elongation is seen in the HAZ area caused by a combination of mechanical penetration and heat input during the process. The microstructure around the drilled holes indicates local deformation triggered by drill bit friction. Despite the presence of frictional heat, the short contact duration of conventional drilling processes tends to produce a narrower HAZ, with grain boundaries experiencing significant mechanical stress.

In the FSSW samples, a more complex material flow pattern is observed. The tool rotation 2200 rpm and axial pressure cause intense plastic deformation. The area in direct contact with the tool experiences grain refinement. This phenomenon is the result of dynamic recrystallization triggered by high thermal energy and deformation, resulting in a finer structure than conventional drilling methods.

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