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Quality of Friction Stir Welding on High-Density Polyethylene-Polypropylene Polymer

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Abstract— One solid-state welding technique that shows great potential in joining polymer materials is Friction Stir Welding (FSW), especially for various polymers like HDPE and PP. FSW can join materials with different mechanical and thermal characteristics without melting the material. The parameters used were a tool rotational speed of 1460 rpm, a feed rate of 30 mm/minute, a plunge depth of 3.84, and a tool tilt angle of 0 degrees for triangular, threaded cylindrical, and tapered groove cylindrical tools. To determine the quality of the welding, the methods used are Non-Destructive Testing (NDT) and Destructive Testing (DT). For NDT, the methods used are visual and radiographic testing. For DT, the tests used are tensile testing, bending testing, hardness testing, and macrostructure testing. From the research results, data were obtained, and the interpretation of the radiographic test showed that the FSW joint of the threaded and grooved tool had no defects, indicating that the FSW joint had good quality. This is supported by tensile strengths of 8 MPa and 4.2 MPa. Meanwhile, the triangular FSW tool showed defects from radiographic testing, such as voids or lack of fusion, with a tensile strength of 1.7 MPa. The highest bending strength obtained from the three tools was for the groove tool, with a bending strength of 16.6 MPa, because the increased material distribution during the welding process created a strong, uniform, and homogeneous surface flow. The bending strengths for the triangular and spiral tools were 15.2 MPa and 5.4 MPa, respectively. The hardness values for the three tools (threaded cylindrical, tapered groove cylindrical, and triangular) were 57.6 SHD, 57.7 SHD, and 60.1 SHD, respectively, which is because the heat from the triangular tool was the highest. The results of the visual test, NDT (Radiography test), are consistent with the macrostructure results: there are no defects in the threads and grooves of the FSW tool, while the FSW tool with a triangular shape has defects in the form of voids.The use of FSW for joining polymer materials in this study is in line with Sustainalbe Development Goals (SDGs) number 4 (Quality Education), 7 (Affordable and Clean energy), 8 (Decent Work and Economic Growth), and 9 (Industry, Innovation and Infrastructure).

Keywords— Dissimilar Joint, Flexural Strength, Hardness Test, Non-Destructive Testing (NDT), Profile pin, Tensile Strength.

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I. INTRODUCTION

The rapid development of manufacturing technology requires joining techniques that are effective, strong, and suitable for the material. The welding process is one of the technologies that still strategically supports industrial demand. Friction Stir Welding (FSW) is one of the most substantial developments among various welding techniques, as it uses friction and plastic deformation processes to create high-quality joints without melting the entire material [1]. Friction Stir Welding (FSW) is a joining technique first introduced by The Welding Institute (TWI) of the UK in 1991, which is a relatively new type of solid-state joining process. [2, 3, 4, 5] FSW-based joint research initially started with aluminum alloys, then expanded to magnesium alloys [6]. In 1999, Clark developed a different Friction Stir Welding (FSW) tool for joining thermoplastic polymer materials, marking the beginning of FSW research on polymers. However, more extensive research on FSW for thermoplastic polymers only began in 2005 and increased after 2009 [7]. Polymer materials, especially thermoplastics, are becoming increasingly popular as alternatives in various industrial sectors due to the global trend toward energy efficiency and weight reduction in construction. Polymers have many benefits, including low density, corrosion resistance, superior moldability, and relatively low production costs [8]. Additionally, it is well known that thermoplastics and thermoplastic composites have a high strength-to-weight ratio, making them ideal for applications in the maritime, automotive, and aerospace sectors [9]. In reality, a 10% weight reduction in cars can increase fuel efficiency by 5% - 7%, which encourages the use of plastic engineering as a substitute for various metal components [10]. However, the use of polymers in the construction sector has several difficulties, especially in terms of joining, which requires techniques that are compatible with their chemical and physical characteristics. The thermoplastic characteristic that can melt at high temperatures and re-harden reversibly when cooled, FSW provides a good bonding

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solution that creates a strong bond between the surfaces of the materials. Van der Waals forces, covalent bonds, and interdiffusion of polymer chains are some examples of adhesion mechanisms used in thermoplastic welding [11]. Unlike metal welding, polymer joining using FSW requires partial melting to enhance the mobility of the polymer chains, allowing for interdiffusion and entanglement between the chains at the interface, creating a strong and secure joint. The ability of FSW in polymers to join materials with very different melting points, such as PC and ABS, is one of its main advantages. Because only one side of the material melts perfectly under such conditions, techniques like ultrasonic welding often do not succeed. By generating consistent localized heating on both sides of the material, FSW can overcome these difficulties and enable joining with the best results [12]. FSW on polymers has emerged as a potential joining method to meet the demands of contemporary industries that prioritize sustainability, strength, and efficiency.

One of the solid-state welding techniques that shows great potential in the integration of polymer materials is Friction Stir Welding (FSW), especially for various polymers such as HDPE and PP. Its main advantage is its ability to unite materials with different mechanical and thermal characteristics without melting the material, creating strong and stable joints and providing opportunities for creative industrial applications [13]. The configuration of the tool and welding parameters tailored to the material properties, such as hardness, ductility, and yield strength, are crucial for the performance of the process. More heat input is required for effective plastic deformation to occur in materials with a high melting point or high thermal conductivity [14]. FSW is suitable for large-scale production automation, providing energy efficiency, and has relatively low equipment costs compared to other alternative approaches [15]. Polymers have a structure in the form of molecular chains with bonds and a random coil configuration, which shows increased flexibility when heated beyond the melting point, allowing the molecular chains to move and bond with each other [16]. An example of this phenomenon is instant noodles, which stick together when dry but become flexible and easily move apart when boiled [17]. To maximize the use of FSW on polymer joints, especially in contemporary structural applications that require high strength and efficiency, a deep understanding of these characteristics is essential.

According to several studies, HDPE joints with high mechanical connection quality that are equivalent to or even exceed the base material can be produced using the Friction Stir Welding (FSW) process with optimal parameters. Optimizing parameters such as tool rotational speed of 1000 rpm, HDPE can achieve tensile strength of up to 14.4 MPa (105% of the base material) and bending strength of around 27 MPa, or 93% of the bending strength of the base material which is 29 MPa. In the study by H. Mehdikhani et al. [22], the results showed that the flexural modulus and impact strength (89%) had slightly decreased, but the mechanical characteristics of the joint were still within acceptable limits and free from serious defects. The addition of Copper oxide nanoparticles (CuO NPs) in the FSW process also significantly increases the mechanical strength. At a tool rotational speed of 200 rpm, the UTS reached 26.63 MPa, or about 84% of the tensile strength of 31.7 MPa of the base material. Strong crystalline bonds can be formed without causing thermal degradation at process temperatures between 78 and 145 °C (30 and 55.7% of the melting point of HDPE) [23]. The selection of tool configuration and specifications with a hot shoe can enhance the quality of similar HDPE joints, with UTS reaching 22 MPa, including other parameters such as plunge depth of 1.0 mm, travel speed of 40 mm/min, and tool rotational speed of 1500 rpm. Meanwhile, conventional FSW tools without a hot shoe achieve only about 60% efficiency, while the use of heated tools (also known as hot shoe tools) or double pin designs can even increase joint efficiency to 96%. The performance of the joints is also influenced by the pin shape, with conical pins offering greater creep strength compared to cylindrical pins [24]. According to Muchhadiya et al. [25, 26], a tool tilt angle of 2° on HDPE results in a maximum elongation (17.36%) and an ideal tensile strength (17.828 MPa), with the tool rotational speed contributing the majority of this effect (45.79%). About 60% of the base material is used in the joint. In PP material, Guangle Fan et al. [27] found that a tool tilt angle of 1° produced the widest mixing zone and maximum tensile strength (66 MPa), while a tool tilt angle of more than 2° actually reduced strength due to more defects. These results validate that the ideal range for enhancing material flow and FSW joint strength in polymers is between 1 and 2°. In tensile and bending tests, it has been proven that tool travel speed in the Friction Stir Welding (FSW) process significantly affects the quality of HDPE joints. In the study by Hazim H et al. [3], it was stated that using a low tool travel speed of 20 mm/min on HDPE with PP strip reinforcement results in a longer thermal exposure period, optimizing material mixing and polymer chain diffusion. The maximum bending strength of 35 MPa (116.66% of pure HDPE) and a significant increase in impact strength, indicating a strong interfacial bond, were achieved by combining a travel speed of 20 mm/min with the addition of 25% PP strips. A moderate travel speed of 30 mm/min, a rotation speed of 1000 rpm, and a plunge depth of 4.1 mm resulted in a yield strength of 16.4 MPa, or 63% of the base material (26 MPa), in HDPE with 2.3% carbon black. According to J.Y. Sheikh-Ahmad et al. [28], due to the short thermal diffusion time, an excessively high travel speed (40 mm/min) at the joint increases the likelihood of defects such as voids, wormholes, and root defects. On the other hand, a low travel speed (20 mm/min) may reduce defects but can cause overheating if not monitored. Then, the research by S. H. Iftikhar et al. [29] shows that the ideal travel speed for the Orbital FSW (OFSW) process on thick-walled HDPE pipes is 9 mm/min, which results in the highest tensile strength of 24.6 MPa, an elongation of 490%, and a flexural modulus of 980 MPa. In OFSW, a high travel speed results in internal defects due to uneven material flow, while a low travel speed causes thermal degradation due to excessive heat. Considering all factors, creating HDPE joints with high mechanical strength, ideal flexibility, and minimal defects requires careful control of travel speed. Therefore, FSW is a very promising joining technique for structural applications on engineering polymer materials such as HDPE and PP due to the combination of process parameter optimization, tool design innovation, and material modification such as the addition of nanoparticles/materials, and dissimilar materials. The parameters used by the researchers are a tool rotational speed of 1460 rpm, a feed rate of 30 mm/min, a plunge depth of 3.84, and a tool tilt angle of 0°.

Welding techniques and process parameters used have a significant impact on defects in the Friction Stir Welding (FSW) process on polymer joints, especially PP and HDPE. Significant defects such as solid inclusions, leading-edge cracks, root defects, and micro-voids were found in the single-sided welding of PP plates due to uneven heat distribution and poor material flow. On the other hand, by creating a more uniform material flow and better heat distribution, the double-sided welding technique can eliminate most of these defects, leaving only a small number in the pin edge areas [30]. Types of defects include voids, improper material mixing, delamination, and interfacial cracks. These occur in the context of different joints between HDPE and PP due to the incompatibility of thermal properties between the two materials, especially when welding at low rotational speeds (700 rpm) and high welding speeds (50 mm/min). Since it has been proven that increasing the rotation speed to 1500 rpm and reducing the welding speed to 25 mm/min significantly enhances mixing and reduces defects, parameter optimization is crucial [31]. The use of ideal parameters, such as a rotation speed of 1500 rpm, a welding speed of 30 mm/min, a tool tilt angle of 2°, and the use of threaded pins that facilitate material mixing and eliminate interfacial gaps, can minimize defects such as interfacial gaps, macro-voids, and non-uniform material flow [29]. Therefore, to create strong, uniform, and defect-minimized structural joints, the performance of FSW on different PP-HDPE joints highly depends on careful adjustment of process parameters and the selection of appropriate equipment. From the presentation of the data above, there is a need for a quality check of the welding results. The ability to identify and manage internal defects, which are often not visually detectable but have a substantial impact on mechanical strength, is a key factor in determining the quality of FSW joints. This is demonstrated by showing that porosity in aluminum FSW joints can be accurately detected using digital radiography [32]. M. S. U. Rahman et al. [33] used the microwave reflectometry method in their research to finding cracks, voids, and delaminations in polymer materials such as HDPE and GFRP. These cracks are detected by changes in microwave characteristics caused by variations in material density. Uneven heat input is the cause of these defects, especially at high travel speeds and tool rotational speeds. According to H. Taheri et al. [34], Non-Destructive Testing (NDT) techniques such as radiography and Phased Array Ultrasonic Testing (PAUT) can identify volumetric defects as small as ~0.0007 mm², while real-time non-contact detection is provided by infrared thermography and laser ultrasonics. According to D.J. Hugget et al. [35], radiography has safety limitations, but PAUT is the recommended option for post-welding because it can accurately detect planar cracks. It has also been shown by L.M. Serio et al. [36] that a combination of NDT (ultrasonic, attenuation, and eddy current) is useful for identifying common FSW defects such as kissing bond. To detect small defects in metal and polymer FSW joints, T. Saravanan et al. [37] and Y.C. Chen et al. [38] used digital processes and Lock-In Infrared Thermography (LI-IRT). Overall, the quality and durability of FSW joints have been greatly enhanced thru defect identification using NDT techniques, especially for critical applications such as pressurized piping systems and the automotive and aerospace sectors. From the presentation, it is evident that quality is closely related to the weld results that can be inspected, one of which is the method that the researchers will use, namely radiographic testing.

A comprehensive mechanical methodology, including tensile and flexural testing, is required to thoroughly characterize the strength and toughness properties of the joints. This approach is important in evaluating the quality of Friction Stir Welding (FSW) joints on polymer materials such as HDPE and PP [39]. states that elongation at break, which is an indicator of material toughness measurement, in tensile testing, maximum tensile strength (Ultimate Tensile Strength/UTS), which represents the maximum stress that the material can withstand before failure, is one of the most crucial mechanical parameters in assessing the structural performance of a joint or material. However, due to thermal degradation, FSW joints often have elongation that is 30–50% lower than the base material. Whether the failure occurs in the base material, HAZ, or stir zone, the location of the failure is also an important indicator for evaluating weld integrity. Brittle fracture caused by overheating in the HAZ and delamination at the interface are common failure modes in tensile testing. Meanwhile, the bending test is crucial for assessing resistance to flexural deformation. Important characteristics such as flexural strength and bend angle indicate how long a joint can withstand a flexural load before breaking. Up to 90% of the base material's flexural strength can even be achieved by FSW polyethylene. Moreover, the bending test is more sensitive than the tensile test in identifying surface defects such as fine cracks, wrinkles, and micro porosity [40]. In this case, tensile testing can produce numerical data on joint strength, but it cannot reveal the distribution of hidden planar defects or surface defects. However, as a simple destructive technique, the bending test can identify cracks and damage that arise from the highest strain during the bending process [41]. Therefore, it is recommended to use both techniques to obtain a comprehensive confirmation of the strength and integrity of the joint. Bending tests are crucial for determining ductility but are also very effective in identifying fusion defects and permanent deformations that may develop into weak points in dynamic or cyclic applications, such as high-pressure pipes. To ensure the structural integrity and long-term durability of FSW joints on polymers, testing strategies that combine tensile and bending tests become very important [42].

The presence of defects as well as the welding techniques and parameters used have a significant impact on the quality of joints produced by HDPE welding. Defects such as holes or inclusions drastically shorten the lifespan of the joints, and the impact increases with the size of the defects, claims H. Lai et al. [43]. In contrast to joints without beads, bead joints are known to have better resistance to long-term deformation (creep). Adjusting the temperature and pressure settings in the butt-fusion welding process can significantly improve the joint quality when welding thick-walled pipes. Additionally, the evaluation technique based on fracture resistance is more applicable to real-world design conditions and more practical, especially in high-pressure applications such as those found in the oil and gas sector [44]. H. Mehdikhan et al. [22] provided a more advanced method by utilizing Orbital Friction Stir Welding (OFSW) along with external heating and a retractable pin tool. It has been proven that this method creates uniform and perfect HDPE joints with an impact toughness of up to 89% and tensile strength up to 105% higher than the base material. These results indicate that polymer FSW, particularly in the form of OFSW, has great potential as a superior welding method for oil and gas industry pipes that require high-strength joints and resistance to extreme operating conditions. From the data presented above, the researchers used the FSW process for welding HDPE-PP materials as a solution for the joining process when applied in the oil and gas sector. According to recent studies, new techniques and equipment can significantly improve the quality of FSW joints on polymers such as HDPE and PP, although non-destructive evaluation still presents substantial challenges.

According to the research by M. S. U. Rahman et al. [33], microwave-based Non-Destructive Testing (NDT) can be used to detect hidden defects that are not visible thru routine visual inspection. These defects include voids, delaminations, and cracks in HDPE pipes and composite materials that can affect the structural integrity of the joints. NDT techniques, including radiography and visual testing, are still rarely used on FSW HDPE–PP joints; instead, these techniques are more commonly used in fusion-based joining processes or composite materials. Meanwhile, the research by M. A. R. Pereira et al. [45] shows that using a stationary hot-shoe shoulder FSW tool heated to ±85 °C on PE material can reduce defects such as porosity and surface burning, achieving joint efficiency of up to 97% with tensile strength comparable to the base material. However, due to the microstructural changes in the stirring zone, the elongation at break value decreased significantly from >850% to around 28%, indicating an increase in brittleness. Using a heated stationary shoulder and a double-side pass technique, M. A. R. Pereira et al. [21] demonstrated in their study that the FSW joint efficiency for PE and PP can exceed 90%. The best results were obtained at a rotation speed to welding speed (w/v) ratio of around 120 rot/mm for PE and less than 60 rot/mm for PP. Innovations such as preheating and external heating have also been proven to reduce joint failures. To improve the performance and reliability of polymer joints in industrial applications, it is crucial to optimize tool design and develop more efficient NDT techniques for FSW joints. Although Friction Stir Welding (FSW) has proven to be an effective method for joining polymer materials such as HDPE and PP, particularly in producing joints with high mechanical strength and homogeneous microstructure, research on the application of Non-Destructive Testing (NDT) methods in evaluating the quality of FSW joints on polymers is still relatively limited. From the previous data presentation, it shows that the FSW process is one of the solutions for joining polymer pipes in the oil and gas sector, but previous research rarely discusses dissimilar materials (PP-HDPE), and there is still a lack of research related to weld quality in FSW polymer materials, especially from inspection results using NDT (Radiographic test). Therefore, this presents an opportunity for researchers to conduct this research. The researcher focuses on "Welding Quality of Friction Stir Welding on High Density Polyethylene-Polypropylene Polymers" with parameters: tool rotational speed 1460 rpm, feed rate 30 mm/min, plunge depth 3.84, and tool tilt angle 0°, NDT using radiography. The tests conducted included tensile testing, bending, hardness, and macrostructure observation.

II. Method

This research was conducted using a laboratory-scale experimental method focusing on butt join type joints thru the Friction Stir Welding (FSW) process between dissimilar thermoplastic materials, HDPE-PP, with the research flow shown in Figure 1. The welding specimens were polymer sheets measuring 125 mm x 57.5 mm x 4 mm as shown in Figure 2. The mechanical properties of each base material (HDPE and PP) are presented in Table 1. In the FSW process, three types of pin profile variations were used: triangular, threaded cylinder, and grooved tapered cylinder, all made from SKD 61 tool steel. The material has undergone heat treatment to achieve a hardness of 55 HRC. The design and dimensions of each pin profile are detailed in Figure 3.

The welding process conducted in this study was carried out using the X 6325 milling machine available in the machining laboratory of Semarang State University, as shown in Figure 4. This machine was utilized as the main drive for the Friction Stir Welding (FSW) process. during the welding process, the operating parameters are kept constant to ensure the reproducibility and validity of the results, namely spindle speed 1460 rpm, travel speed 30 mm/min, tilt angle 0º, plunge depth 3.90 mm, complete parameters can be seen in Table 2.

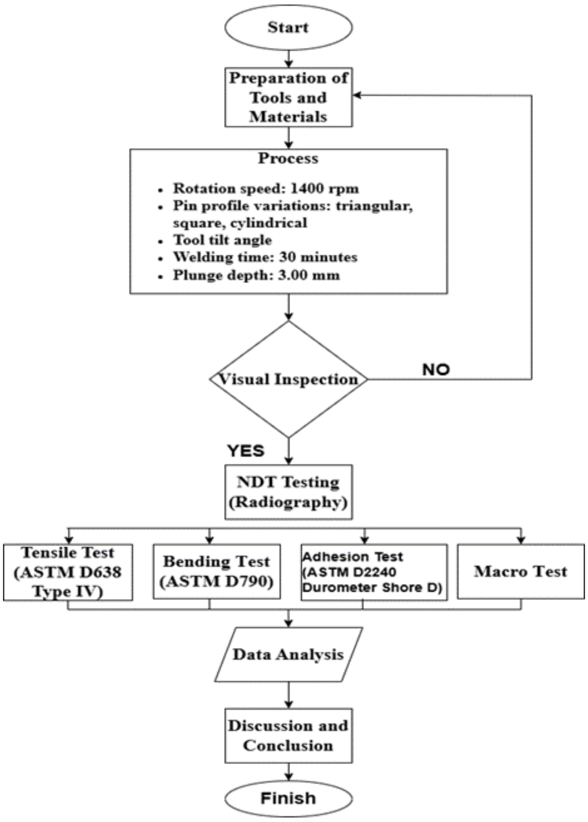

Figure 1. Research Flowchart

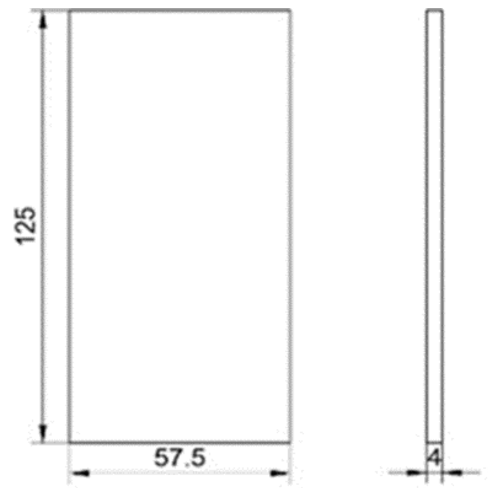

Figure 2. HDPE-PP Material Dimensions

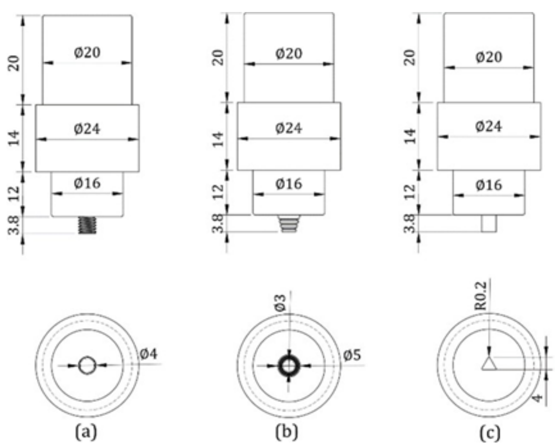

Figure 3. (a) Threaded Cylindrical (b) Tapered Grooved Cylindrical (c) Triangular

TABLE 1.
MECHANICAL PROPERTIES HDPE-PP

Mechanical Properties	Tensile strength (MPa)	Flexural strength (MPa)	Hardness (SHD)
High density polyethylene	22,5	26.7	56.6
Polypropylene	27.5	40.5	69.5

These three parameters were chosen based on preliminary studies and literature references to fall within the optimal range for thermoplastic polymer welding. As the main variable, three types of pin profile variations were used: triangular, threaded cylinder, and tapered grooved cylinder. These pin-shaped variations aim to evaluate the influence of tool geometry on the quality of plastic mixing and the mechanical performance of HDPE-PP joints.

TABLE 2.
FRICTION STIR WELDING PARAMETERS

Kecepatan Spindel	1460 rpm
Travel Speed	30 mm/min
Tilt Angle	0°
Plunge Depth	3,90 mm
Pin Profil	Triangular, threaded cylinder, & grooved tapered cylinder

HDPE and PP material sheets are positioned to form a butt joint on the workbench, then clamped using U-clamps to ensure the joint remains stable during the welding process. Next, the profile pin is precisely installed on the spindle of the X-6325 milling machine. The travel speed parameter is automatically adjusted according to the values specified in the experimental planning. The welding process begins with turning on the machine, followed by the gradual lowering of the profile pin until it penetrates the workpiece surface according to the predetermined plunge depth, which is 3.90 mm. During the process, the pin moves along the joint line, generating friction and pressure that cause the HDPE and PP materials to undergo thermal softening. The softened material is then mechanically mixed by the rotation of the pin, forming a solid-state bond between the molecules without going thru the complete melting phase. This process continues until it reaches the end point of the joint line. A visual illustration of the welding process is presented in Figure 5.

Figure 4. Milling Machine

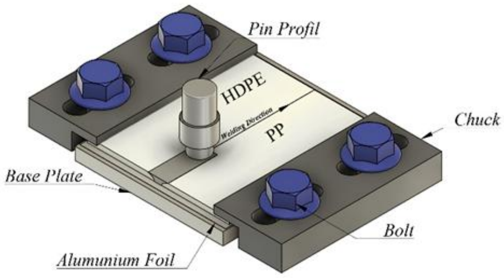

Figure 5. Illustration of Friction Stir Welding of HDPE-PP

To ensure that the produced FSW joints have good structural quality and are free from internal defects, testing is conducted using Non-Destructive Testing (NDT) and Destructive Testing (DT), as this process has the potential to produce typical defects such as wormholes, kissing bonds, and lack of penetration that are not detected thru regular visual inspection and affect the mechanical properties of the joints. The Non-Destructive Testing (NDT) used in this research is Radiography conducted at the Radiography-NDT Laboratory of the Indonesian Nuclear Technology Polytechnic. The radiographic method has proven effective in detecting very small volumetric defects, even as small as 0.0007 mm². Generally, radiography is an effective method for detecting post-FSW volumetric defects in polymers, especially dissimilar polymers HDPE and PP. The testing process is visually shown in Figure 6.

Figure 6. Radiographic NDT Testing Process

Additionally, macro structure observations were conducted using a digital microscope equipped with an integrated camera to record and store observation images on a computer. The purpose of this observation is to analyze the morphology of the joint interface, as well as to identify defects that appear on the joint, and to identify defects that appear in the three main zones of the weld, namely the Advancing Side (AS), Stir Zone (SZ), and Retreating Side (RS). This macro analysis is important for examining the quality of material mixing and the potential imperfections in the bond between polymer surfaces.

The types of Destructive Testing (DT) used include macro visual observation, tensile testing based on the ASTM D638 Type IV standard [22], Bending Test ASTM D790 Three Point [3], and Hardness test ASTM D2240 Durometer Shore-D [46]. The purpose of conducting these tests is to determine the mechanical characteristics of the welding material, including maximum tensile strength, elastic modulus, flexural deformation, and surface hardness. The specimens for each type of test are presented in Figure 7.

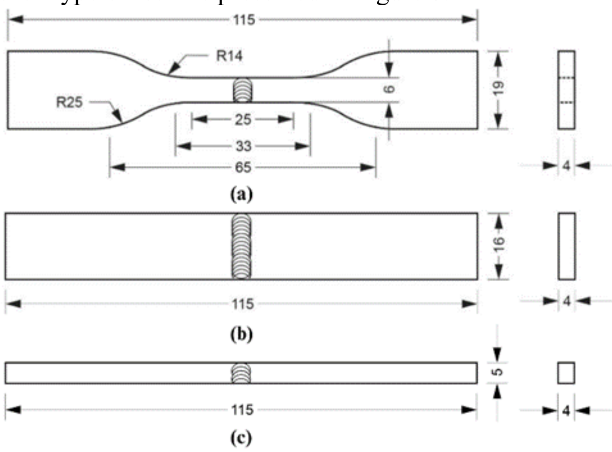

Figure 7. Specimen (a) Tensile Test (b) Bending Test

Tensile testing aims to evaluate the variation in pin profile geometry against the maximum tensile strength, yield point, material elongation, and elastic modulus of the FSW welded joint on dissimilar HDPE-PP materials. Meanwhile, bending tests are conducted to assess the toughness of the joint under bending loads. Not only does this test provide a quantitative value of flexural strength, but it also allows for the visualization of deformation and surface cracks due to planar defects or voids in the stir zone, which is crucial for ensuring the structural quality of the joint. Tensile and bending tests were conducted using the Zwick/Roell Z020 universal testing machine. The tensile and bending tests were performed at room temperature with a tensile speed of 3 mm/min for the Tensile Test, while 2 mm/min for the Bending Test. The testing procedures are visually displayed in Figure 8.

Figure 8. (a) Bending test (b) Tensile test

Hardness testing is conducted to determine how strong the surface of the FSW joint material is against penetration or local deformation caused by compressive load. In this study, hardness was tested using the Shore-D Durometer method according to ASTM D2240 standards. This method is commonly used to measure the hardness of thermoplastic materials such as HDPE and PP. The test was conducted at several cross-sectional points of the joint, covering the Base Material (BM), Advancing Side (AS), Stir Zone (SZ), and Retreating Side (RS) areas. This is done to produce a picture of hardness distribution along the weld path. The obtained hardness values indicate changes in mechanical properties caused by thermomechanical effects during the FSW process, such as thermal softening, molecular chain reorientation, or inhomogeneity in the mixing of dissimilar materials. This test is important because significant variations in hardness between regions can indicate local structural weaknesses such as low wear resistance or crack initiation points. The results of the hardness test are also used as supporting data to interpret the behavior of the joints under tensile and bending loads that were previously tested mechanically.

III. RESULTS AND DISCUSSION

Tool on dissimilar HDPE-PP materials, mechanical property tests of the FSW joints were conducted. The types of tests performed include tensile, bending, hardness, macro photo analysis, and NDT. The test data results were analyzed and then presented in the form of images, graphs, and explanations of the data analysis. Temperature measurements were taken during the Friction Stir Welding (FSW) process because temperature is the main indicator of the frictional heat and plastic deformation heat generated from the friction between the pin tool and the polymer material. The size of the stir zone (SZ), thermo-mechanically affected zone (TMAZ), and Heat Affected Zone (HAZ) is influenced by the amount of heat generated by various pin profiles [47]. In addition, proper temperature control is carried out to help achieve good mixing and molecular bonding in the stir zone. Figure 9 shows three stages of temperature measurement, namely, initial, middle, and final, during the FSW process to determine the temperature stability throughout the FSW process. In Figure 10, the temperature from the 3 pin variations can be seen; the triangular pin tends to generate the highest heat, which can allow for more thorough material mixing but also risks exceeding the polymer degradation temperature.

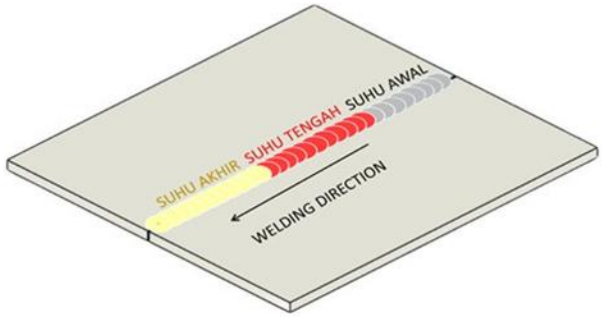

Figure 9. Welding Temperature Schema

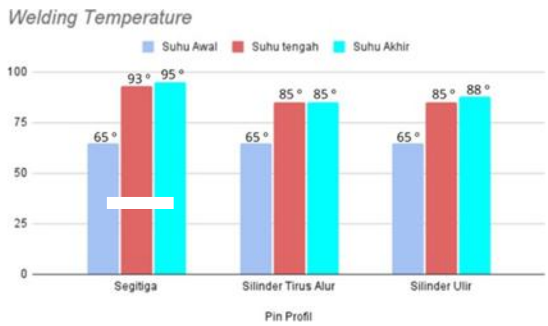

Figure 10. Welding Temperature

1.1. Visual Examination

The welding results on the polymer specimen were visually observed from the surface and bottom. In Figure 11, the results of the FSW tool welding on the front groove show that there are imperfections in the form of excessive excess flash on the welding seam side, which is evident from the rough-textured material protruding from the joint area.

Figure 11. FSW Tapered Grooved Tool

In Figure 12, the results of the FSW welding of the front triangular section show imperfections in the form of excessive flash on the welding seam side, which is visible from the rough-textured material protruding from the joint area. The surface roughness appears uneven, indicating an uneven heat distribution during the welding process, resulting in voids and areas that are not perfectly joined, leaving gaps. The back surface has imperfections in the form of lack of fusion.

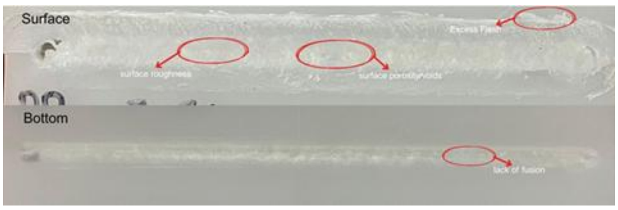

Figure 12. FSW Triangular Tool

In Figure 13, the results of the FSW welding of the front thread show that there are imperfections in the form of overheating due to excessive frictional heat at certain points, excessive flash on the side of the weld path, which is visible from the rough-textured material that protrudes from the joint area. The back surface does not have any defects.

Figure 13. FSW Threaded Cylindrical Tool

The three polymer welding results (FSW tool Groove, Triangle, and Thread) show imperfections in the surface area in the form of excess flash, while the root area of the FSW groove and thread tools have no defects, but the triangle tool has a defect in the form of lack of fusion. Therefore, further NDT testing is needed to identify internal defects thru radiographic testing.

1.2 Non-Destructive Testing (NDT)

Non-Destructive Test (NDT) using X-ray radiography method has been conducted on three types of Friction Stir Welding (FSW) joint geometries on polymer materials with a thickness of 3-4 mm. The three joint designs tested are straight groove (FSW-Tool Alur), triangular (FSW-Tool Segitiga), and threaded (FSW-Tool Ulir). This test aims to evaluate the quality of the joint in terms of homogeneity and the presence of defects or discontinuities in the weld joint.

1.2.1 FSW Tool Tapered Grooved Cylindrical

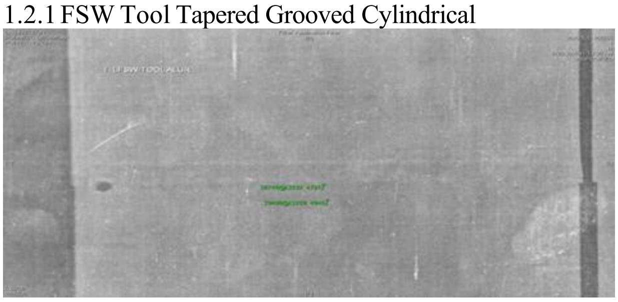

Figure 14. Radiography Results of Tapered Grooved FSW Tool

Radiographic results show that the FSW joint with a straight groove design has the best joint quality among the three types tested. The density value between the weld metal and the base material shows almost no significant difference, indicating that the joining process is proceeding homogeneously and thoroughly. No indications of cavities, porosity, or other defects were found in this joint. It can be concluded that the straight groove joint produces a good metallurgical bond and can serve as a standard reference for FSW weld geometry on polymers [50].

1.2.2 Tool Triangular

The joint with a triangular design shows relatively good results, but indications of defects or discontinuities are still found in some areas. These defects are detected thru a striking difference in density in certain areas, reaching 1438 gv, indicating the presence of cavities or lack of fusion between materials. The darker color in the radiographic film results indicates the presence of internal gaps or pores that have not been completely filled. This indicates that although most of the joints have formed, there are still areas that have not fully bonded. The presence of this discontinuity can become a mechanical weak point that potentially reduces the tensile strength and dynamic load resistance of the joint [21, 29].

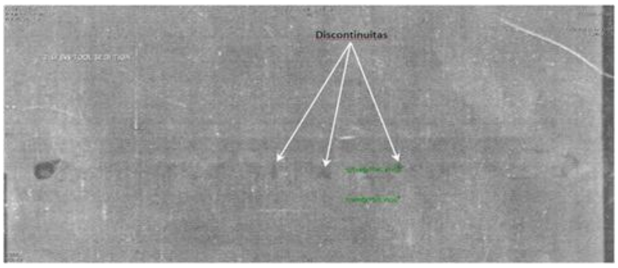

Figure 15. Radiography Results of Triangular FSW Tool

1.2.3 FSW Tool Threaded Cylindrical

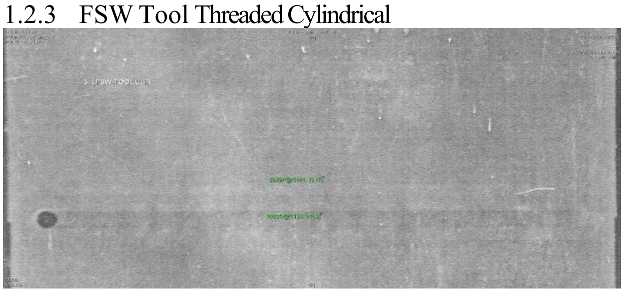

Figure 16. Radiography Results of Threaded Cylindrical FSW Tool

The radiographic results on the threaded joint show that, in general, the joint is well-formed and homogeneous, but there is a density difference of 1028 gv between the weld area and the base material. This difference indicates that the thickness of the weld is slightly thinner compared to the base material, which could be caused by uneven axial pressure or an incomplete material mixing process during the FSW process. Although no large voids or significant cracks were found, this thickness difference remains an indicator of variations in joint quality that could affect long-term performance [20].

These results confirm that the quality of FSW joints in polymer materials is greatly influenced by joint design, plunge depth, and the distribution of heat and pressure during the welding process. The success of the process is highly determined by process parameters such as tool rotation speed, feed rate, and the geometric design of the tool and the welded material. Radiography as an NDT method has proven effective in identifying non-visual internal defects, such as porosity, incomplete fusion, and density inhomogeneity, without damaging the specimen[51].

1.3 Tensile Test

The tensile testing process was conducted according to the ATMI Surakarta Polytechnic lab standards, specifically ASTM D638 Type IV, as shown in Figure 8. The machine data used in this test is the Zwick Z020. The tensile test specimen is placed in the machine chuck with a pre-load of 0.5 N, a tensile modulus speed of 3 mm/min, a test speed of 3 mm/min, and a grip-to-grip separation at the start position of 65.00 mm. The tensile test specimens are made according to the ASTM D638 Type IV standard. The Ultimate Tensile Strength (UTS) values for dissimilar FSW joints in HDPE – PP material are obtained.

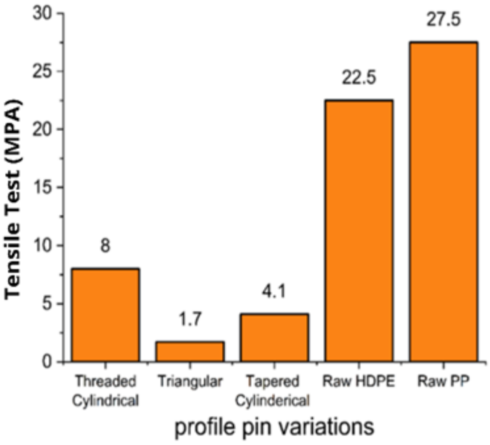

Figure 17. Tensile Test Results Chart

In Figure 17, the tensile test results are displayed where the threaded cylindrical pin profile shows a maximum tensile strength of 8 MPa with an elongation value of 1.8%. This is consistent with the radiographic test results, which indicate no defects and that the joint is formed well and homogeneously. However, there is a density difference of 1028 gv between the weld area and the base material. The temperature is quite high but does not cause thermal degradation due to the precise control of transverse speed and offset, allowing for good material flow and strong polymer molecular bonding. Thus, the combination of the material flow effect due to the thread and the temperature increase provides the best tensile strength for the threaded cylindrical joint [52]. Followed by the tapered cylindrical pin at 4.1 MPa with an elongation of 1.2%, the tapered cylindrical pin shows material flow more downward, and at high rotational speeds, it causes cavities on the surface. The impact is a weaker joint with the tapered cylindrical pin under certain conditions [53], and the triangular pin has the lowest tensile strength, which is 1.7 MPa, and an elongation of 1.7%. This is consistent with the radiography test results, which show defects detected thru a striking difference in density in certain areas, reaching 1438 gv, indicating the presence of voids or lack of fusion between materials. This is caused by excessively high temperatures, over-stirring effects, and void formation due to the sharp edges of the pin, which increase frictional heat at several points, triggering a high-temperature gradient that affects the material's viscosity, leading to suboptimal flow and triggering voids in the joint path [47]. Threaded cylindrical pins are more capable of creating good tensile strength compared to other shapes. It can be concluded that the shape and design of the pin profile also have a significant impact on the quality of the joint.

1.4 Bending Test

Bending tests using the three-point bending method are used to examine the extent to which the strength of the weld joint can withstand bending loads without cracking. When the load is applied, the specimen will experience internal forces in the form of tensile and compressive stresses, which play a crucial role in determining the joint's resistance to flexural deformation [54]. The results of the bending test can be seen in Figure 18, which illustrates how variations in the pin tool shape during the Friction Stir Welding (FSW) process affect the flexural strength of the joint between HDPE and PP materials.

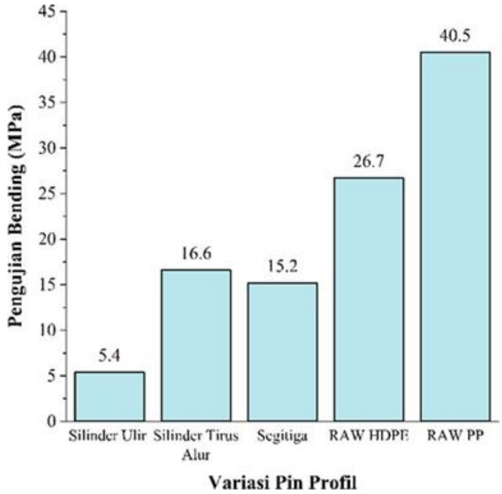

Figure 18. Bending Test Results Chart

1.5 Hardness Test

A significant impact on the mechanical performance of the weld. The order of strength from lowest to highest is: Threaded Cylindrical, Triangular, Tapered Cylindrical. The lowest flexural value of 5.4 MPa was obtained from the use of a threaded pin tool. This low value is caused by uneven material flow due to the threaded geometry.

Meanwhile, the triangular profile yields better results, namely 15.2 MPa, because it can create more intense material mixing during the welding process. However, the sharp angles of the triangular shape can cause stress concentration, potentially becoming a starting point for failure. The most optimal result was achieved by the tapered cylindrical profile, with a bending strength value of 16.6 MPa. This indicates that the axial groove design on the tapered cylindrical tool can improve material distribution during the welding process, creating a strong, uniform, and homogeneous surface flow, thereby resulting in better structural integrity of the stir zone (SZ) in the outer joint area, which plays an important role in resisting bending deformation. When the pin stirs the base material, friction and plastic deformation generate heat that softens the material without melting it, thereby avoiding metallurgical defects. This is equivalent to the previously measured temperature, which shows that the tapered cylindrical pin does not generate excessive heat. The tapered cylindrical pin dissolves some of the precipitate in the stir zone, and thru the dynamic recrystallization process, fine, uniform grains are formed. The presence of precipitate has a greater influence on grain boundary formation compared to strain hardening, so this pin profile produces a stronger joint compared to other profiles, while the threaded cylinder and triangular pins produce less ductile joints [55, 56].

For comparison, materials that did not undergo the joining process (RAW HDPE and RAW PP) show much higher flexural strength values, namely 26.7 MPa and 40.5 MPa, respectively. This is due to the absence of heat and mechanical deformation that can degrade the original properties of the material. PP generally has stronger mechanical characteristics compared to HDPE, as reflected in the difference in their flexural stress values.

The graph of the FSW (Friction Stir Welding) hardness test results between HDPE and PP with variations in tool profiles in Figure 19 shows that the variation in tool shape affects the joint hardness value.

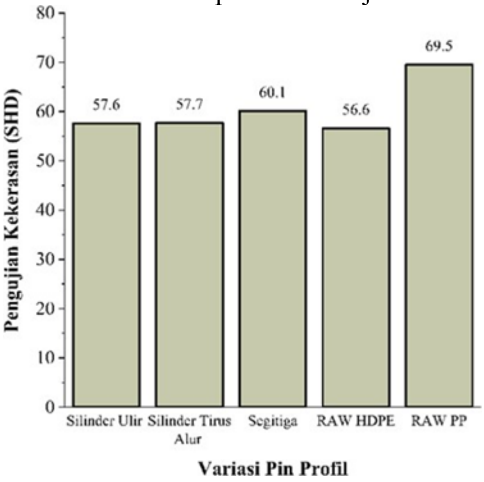

Figure 19. Hardness Test Results Chart

The hardness values obtained from the Threaded Cylindrical, Tapered Cylindrical, and Triangular profiles are 57.6 SHD, 57.7 SHD, and 60.1 SHD, respectively. For comparison, the hardness value of raw HDPE material is 56.6 SHD, while raw PP shows the highest hardness at 69.5 SHD. This indicates that PP naturally has higher hardness compared to HDPE. The FSW process itself can increase hardness thru mechanisms of plastic deformation and dynamic recrystallization that occur due to friction and pressure during welding [57].

The tool profile plays an important role in the effectiveness of the process. The tool with a triangular profile produces the highest hardness value among the other variations, indicating that this profile is capable of achieving more optimal material mixing and thermomechanical flow. Unlike circular pins, the sharp angles of non-circular profiles such as triangles generate more heat and reach higher peak temperatures, creating an intensive stirring zone, thereby enhancing the microstructural homogeneity and weld density [54]. Meanwhile, the Threaded and Tapered Cylindrical profiles only provide a relatively small increase in hardness compared to pure HDPE, indicating that the material flow and heat distribution generated are less optimal and less crystallized [56]. Therefore, it can be concluded that the Triangular profile is the most effective tool in increasing the hardness of the FSW joint between HDPE and PP because it generates the most heat, thereby promoting recrystallization that can enhance hardness [57].

1.6 Macrostructure Observation

1.6.1 *Tool* Tapered Grooved Cylindrical

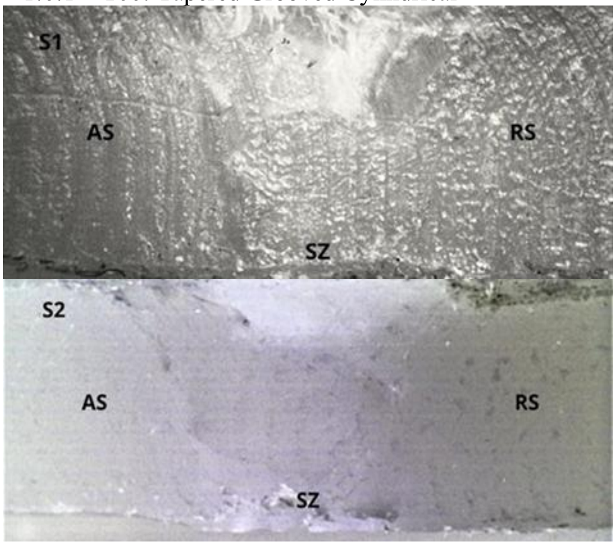

Figure 20. Macrostructure Results FSW Tool Tapered Cylindrical

Macro observation of the Friction Stir Welding (FSW) joint of High Density Polyethylene (HDPE) and Polypropylene (PP) materials with groove design in Figure 20 shows the formation of a homogeneous stir zone (SZ) between the advancing side (AS) and the retreating side (RS). The SZ contour appears uniform with a clear transition to the thermo-mechanically affected zone (TMAZ) and the base material, without indications of significant visual defects such as voids, tunnel defects, or delamination. These results are reinforced by radiographic tests showing that the weld zone density values approach those of the base material, indicating a homogeneous and thorough material union and the absence of internal defects such as porosity or cavities. These findings are consistent with previous research that states that groove geometry in the polymer FSW process can enhance mixing efficiency and minimize air entrapment in the joints [29].

Mechanically, the joint with this groove design produced a tensile strength of 4.1 MPa and a flexural strength of 16.6 MPa, indicating an improvement in joint integrity compared to the groove-less configuration in previous research [21]. This improvement is attributed to the optimization of material flow due to the groove design, which expands the plastic area and enhances mechanical interlocking in the weld zone. Based on the consistency between macro results, radiography, and mechanical tests, it can be concluded that the straight groove design in FSW HDPE–PP is capable of producing high-quality joints, minimal defects, and adequate structural strength for polymer-based engineering applications, and is recommended as a standard reference for the geometry of polymer FSW welds with significant thermal property differences.

1.6.2 *Tool* Triangular

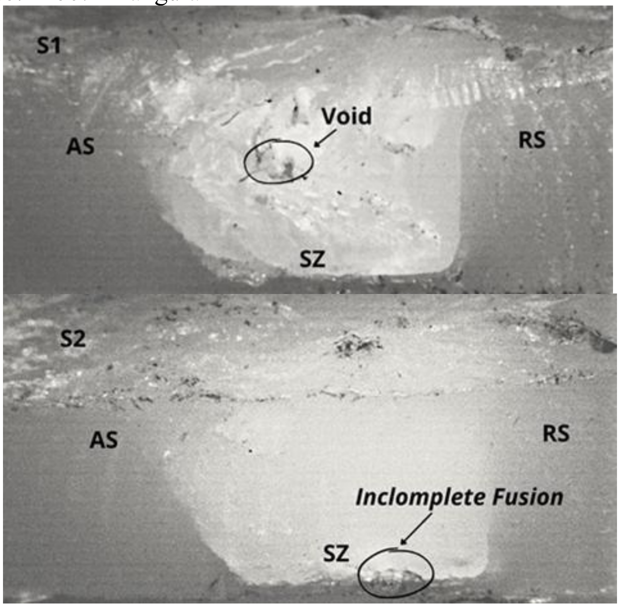

Figure 21. Macrostructure Results FSW Tool Triangular

Macroscopic observation of the Friction Stir Welding (FSW) joint between HDPE and PP with a triangular groove design in Figure 21 shows the formation of the stir zone (Stir Zone/SZ), but indications of incomplete fusion at the base of the SZ and the presence of voids in the middle area were found. This indicates the occurrence of plasticization and uneven material mixing, possibly due to suboptimal heat distribution or insufficient axial pressure [21]. Radiographic results reinforce this observation by displaying density differences of up to 1438 GV and darker film areas, indicating internal gaps or open porosity. The presence of this discontinuity has the potential to be the starting point of structural failure, reducing tensile strength and resistance to dynamic loads.

The tensile strength of the joint only reaches 1.7 MPa, much lower than joints with more homogeneous geometry, while the flexural strength is recorded at 15.2 MPa, which may be more tolerant of local defects. This condition is consistent with findings in the polymer FSW literature review, which indicates that parameters such as tool geometry, tilt angle, and thermal conditions significantly influence defect formation and joint efficiency [21]. Therefore, optimizing process parameters such as using tools with the appropriate pin and shoulder, as well as adjusting speed and heat settings, is necessary to minimize defects and improve the quality of FSW joints in HDPE–PP polymer materials.

1.6.3 *Tool* Threaded Cylindrical

Macro observation of the Friction Stir Welding (FSW) joint using a threaded tool on HDPE–PP Figure 22 shows the formation of a relatively homogeneous stir zone (Stir Zone/SZ), although there are morphological deviations at the top (S1 and S2) indicating that the material flow from the advancing side (AS) to the retreating side (RS) is not yet optimal. This phenomenon is consistent with the radiographic results showing a density difference of ±1028 GV between the weld area and the base material, indicating that the joint thickness is slightly thinner compared to the base material. Although no macro defects such as porosity or significant cracks were identified, the variation in thickness and differences in microtexture have the potential to affect the long-term consistency of mechanical properties. The mechanical test results confirm these findings, where the tensile strength of the joint was recorded at 8 MPa and the flexural strength at 5.4 MPa, indicating that although the joint appears visually well-formed, its mechanical quality still requires optimization, particularly thru the adjustment of process parameters such as axial pressure, rotation speed, and material flow pattern. These findings are consistent with previous research that emphasizes the significant impact of pin geometry on the integrity of joints in polymer FSW [58]. Previous studies also highlight the importance of controlling process parameters to minimize defects and enhance joint strength [29].

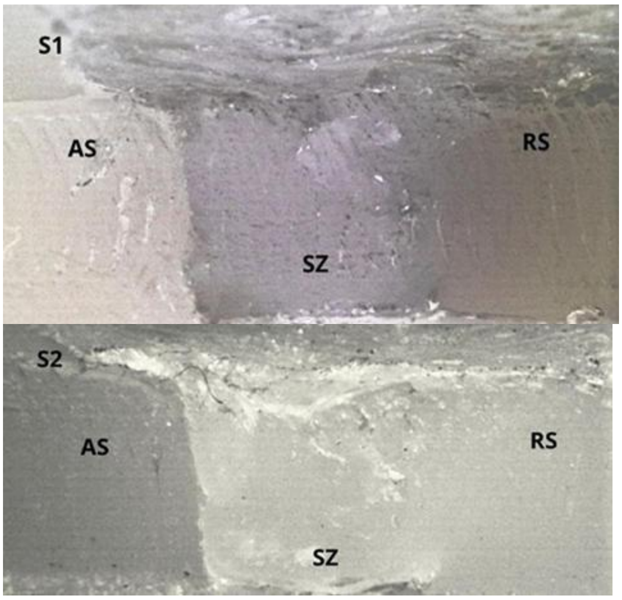

Figure 22. Macrostructure Results FSW Tool Threaded Cylindrical

IV. CONCLUSION

From the research, it can be concluded that the welding quality with the parameters of tool rotational speed 1460 rpm, feed rate 30 mm/min, plunge depth 3.84, and tool tilt angle 0° from the triangular, threaded, and grooved tools can be seen from the visual data of the three tools. In the surface area, there is excess flash, while in the root area, the FSW with the threaded and grooved tools has no defects, but the FSW with the triangular tool has a defect in the form of lack of fusion. The radiographic inspection results show that the FSW joints with the threaded and grooved tools do not have defects, indicating that these FSW joints have good joint quality. This is supported by a tensile strength of 8 MPa and 4.2 MPa. Meanwhile, the triangular FSW tool shows defects from the radiographic test in the form of voids or lack of fusion with a tensile strength of 1.7 MPa. The bending strength obtained from the three tools was highest in the groove tool with a bending strength of 16.6 MPa. This is due to the improved material distribution during the welding process, creating a strong, uniform, and homogeneous surface flow. Meanwhile, the bending strengths of the triangular and threaded tools were 15.2 MPa and 5.4 MPa, respectively. The hardness values of the three tools—threaded, groove, and triangular—were 57.6 SHD, 57.7 SHD, and 60.1 SHD, respectively, due to the highest heat from the triangular tool. The results of the visual test and NDT (Radiography test) align with the macrostructure results, where the FSW tools with threads and grooves show no defects, while the FSW triangular tool has defects in the form of voids. The mechanical strength indicates that the welding quality is achieved with the threaded and grooved tools, showing that the tool design affects the mechanical strength of the joint.

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