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Characteristics of Pin Profile Variations in Friction Stir Welding (FSW) Joints of High Density Polyethylene (HDPE) And Polypropylene (PP) on Mechanical Properties

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ABSTRACT

In the Friction Stir Welding (FSW) process, the pin profile is one of the key factors in determining the quality of the joint because it directly affects the material flow in the joint area and the heat distribution generated during welding. Therefore, this study aims to determine the characteristics of pin profile variations in high-density polyethylene (HDPE)-polypropylene (PP) joints. Three types of pin profiles were used: threaded cylindrical pins, triangular pins, and grooved tapered cylindrical pins. The feed rate was 15 mm/min, the feed depth was 3.96 mm, and the rotating speed was 930 rpm. Hardness, tensile, bending, and macro-photo tests were conducted to determine the mechanical properties of the joints. The results showed that the grooved tapered cylindrical profile pin obtained the highest average value for hardness at 62.7 SHD, and tensile strength at 11.1 MPa. The lowest average values were obtained for the threaded cylindrical profile pins at 61.6 SHD, and 4.2 MPa. Flexural strength with the highest average value of 13.9 MPa was obtained for the triangular profile pin, while the lowest average value of 4.9 MPa was obtained for the threaded cylindrical profile pin. The strength test results, and macro photographs show that the shape and design of the profile pins play an important role in heat generation through friction as well as the control of material flow dynamics, which directly determines the structural integrity and mechanical properties of the joint.

Keywords: Poolymer, Friction Stir Welding, Welding, Butt Joint

INTRODUCTION

Industrial challenges in designing strong, lightweight, economical, and efficient structures are driving the increased use of polymeric materials [1][2]. Flexibility in manufacturing design and better productivity, polymer materials are widely applied in most sectors of modern industry [3][4]. The use of lightweight materials instead of heavy materials can reduce vehicle weight by 10%, reduce CO_2 emissions, and save fuel by about 5-7% [5][6].

Innovations in the production of lightweight parts made of polymers, as well as the development of vehicle structures using polymer composite materials have been applied in several vehicle models, such as the Alfa Romeo 4C, BMW 7 series, and Chevrolet Corvette Z06 [7][8]. Meanwhile, in the aviation industry, the Boeing 787 aircraft uses more than 50% polymer composites in its structure, which can reduce the weight of the aircraft by 20% compared to the use of aluminum [9].

As theuse of polymer materials in various engineering applications increases, the development of polymer joining methods is continuously pursued to improve the reliability and efficiency of the joints. The joining of polymer materials generally utilizes three main methods; adhesive bonding mechanical bonding, and welding [10][11]. Each method has different characteristics and applications, but there are constraints in its application.

The poor thermal properties and low melting temperatures of polymer materials are the reasons that conventional welding cannot be applied [12]. In addition, polymer joining using conventional methods is considered ineffective due to its poor mechanical properties. For example, adhesive bonding has a negative impact on the environment due to chemicals, and mechanical bonding can increase weight and cause residual stresses that affect structural integrity [13][14].

In several industrial sectors, Friction Stir Welding (FSW) is a widely used welding technique for fabricating structural components [15]. This method is effective for joining similar and dissimilar polymers, thanks to its simple process, and is more economical than other methods [16]. In its process, Friction Stir Welding (FSW) uses a rotating tool to generate heat and soften the material in the joint area. The tool moves along the joint line, mixing the softened material and forming a solid-state bond without melting the material [9]. Although it offers many advantages, the Friction Stir Welding (FSW) process, especially on different polymer materials, still faces challenges in optimization to produce quality joints.

The results of research conducted on High-Density Polyethylene (HDPE), and Polyvinyl Chloride (PVC) sheets to determine the impact of FSW welding process parameters on mechanical properties.

Showed that hardness decreased when the welding rate speed increased, then increased again with increasing rotational speed [17].

Another study on optimization of FSW welding process parameters on Polymethyl Methacrylate (PMMA), Polypropylene with 20% carbon fiber, Nylon-6, Polypropylene with 30% glass fiber, pure Polypropylene joints. They concluded the welding rate Travel Speed (Ts), Plunge Depth (Pd), tool Rotation Speed (Rs), affect the mechanical strength of Friction Stir Welding (FSW) joints, and keep the material heat in a plastic state (without melting) during the welding process. As the rotational speed increases the heat generation increases, while the amount of heat decreases by decreasing the rotational speed [18][19]. The shape and inclination of the tool probe play an important role in the stirring and heat effect during FSW welding [20][21][22][23].

The pin profile is key in the Friction Stir Welding (FSW) process, where the pin geometry plays a role in generating heat as well as controlling material flow. This factor directly affects the shape and mechanical properties of the joint [24][25]. Many studies have been conducted to investigate the use of Friction Stir Welding (FSW) joints in various polymer material combinations, such as; HDPE-PA-16[26], PLA Plus-High Density Polyethylene [1], Polyethylen-Polypropylene [27], UHWMPE-Polypropylene[28], ABS-PP [29]. This study is important in manufacturing engineering especially in an effort to reduce production costs, lighten structures, and optimize the advantages of each material.

Differences in the rheological properties of polymers, such as melt viscosity, affect the material flow behavior during the FSW process and are an important consideration in the design of pin profile geometry. However, research on the effect of pin profile on the joint quality of different polymers, particularly HDPE-PP, is limited. Therefore, this study aims to analyze the characteristics of pin profile variation on the mechanical properties of FSW butt joints in 4 mm thick HDPE-PP plates.

RESEARCH METHOD

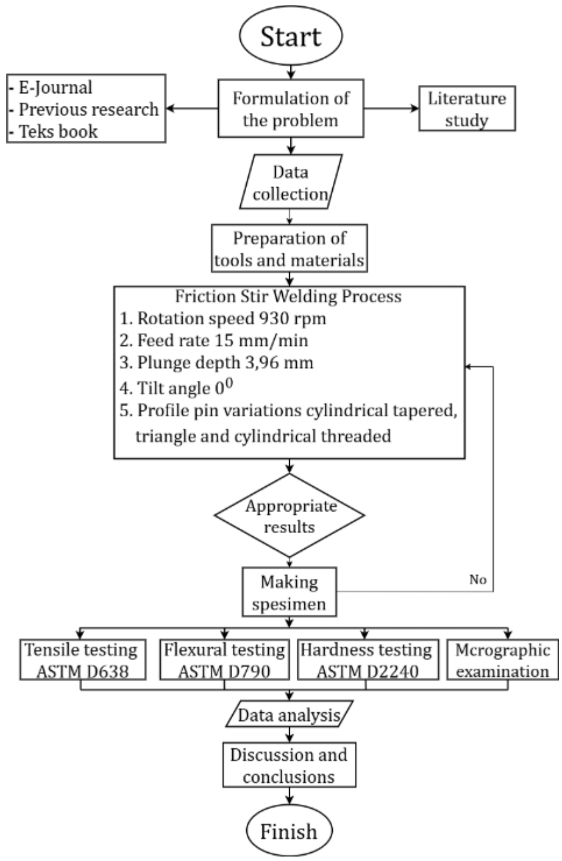

Figure 1. The flow chart of research

The main materials of this study are High-Density-Polyethylene (HDPE) - polyproylen (PP) polymer sheets, which have dimensions of 125 mm x 57.5 x 4 mm, shown in Figure 2. Meanwhile, the physical and mechanical properties of both polymers are shown in Table 1.

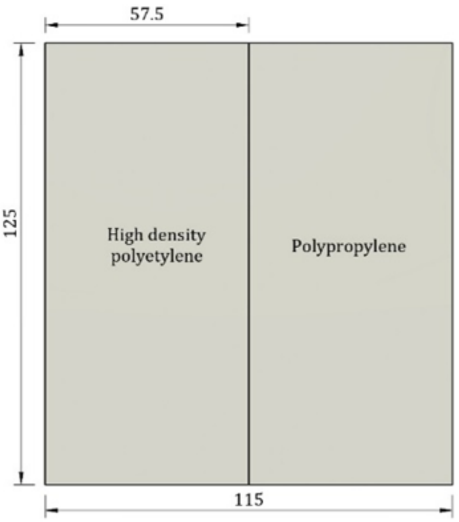

Figure 2. HDPE-PP material dimension

The variation of pin profile shapes used consisted of threaded cylinder, groove cone cylinder and triangle, which were made of SKD 61 alloy tool steel and had been heat treated to a hardness of 55 HRC. This research uses experiments in the Mechanical Engineering laboratory of Semarang State University with a descriptive statistical analysis approach.

Table 1. Mechanical properties HDPE-PP

Mechanical Properties	Tensile strength (MPa)	Flexural strength (MPa)	Hardness (SHD)
High density polyethylene	19	24.4	58.4
Polypropylne	30.9	47.2	71.8

The purpose of the study was to determine the characteristics of the research variables and describe the data on the variation of pin profile shapes on the quality of HDPE-PP Friction Stir Welding (FSW) joints. The target of the test research results in the form of tensile, strength, and hardness tests presented in graphical form. The geometry shape of the FSW pin profile, can be seen in figure 3.

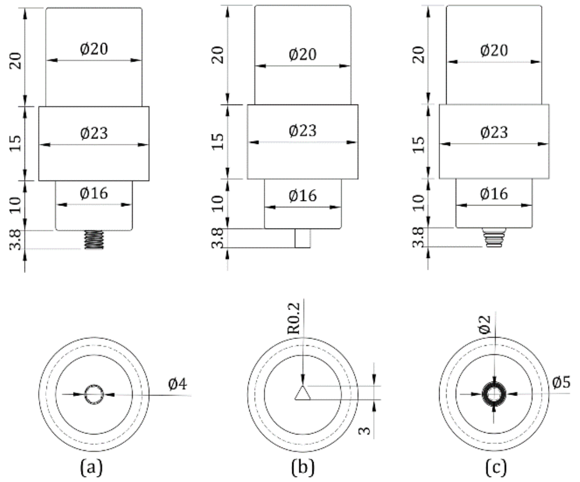

Figure 3. Pin profile variation (a) threaded cylindrical (b) grooved tapered cylinderical (c) triangular

Parameters using a rotational speed of 930 rpm travel speed of 15 mm/min, a plunge depth of 3.96 mm, and a tilt angle of 0° constantly to determine the characteristics of three variations of pin profile shapes; threaded cylindrical, triangular, and grooved tapered cylindrical, FSW process parameters can be seen in Table 2.

Table 2. FSW process parameters

Pin profil	Threaded Cylindrical, Triangular and Grooved Tapered Cylinderical
Rotation speed (rpm)	930
Fede rate (mm/min)	15
Plunge depth (mm)	3.96
Tilt angle (0^0)	0

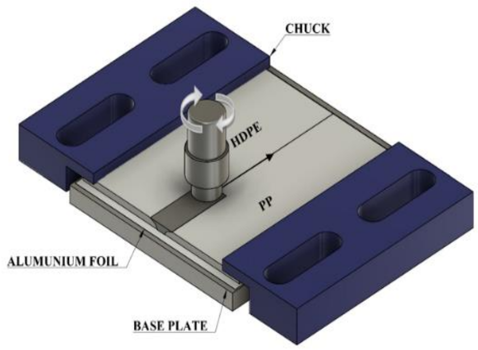

Figure 4. Is a schematic representation of the FSW process used to join HDPE-PP materials in this study.

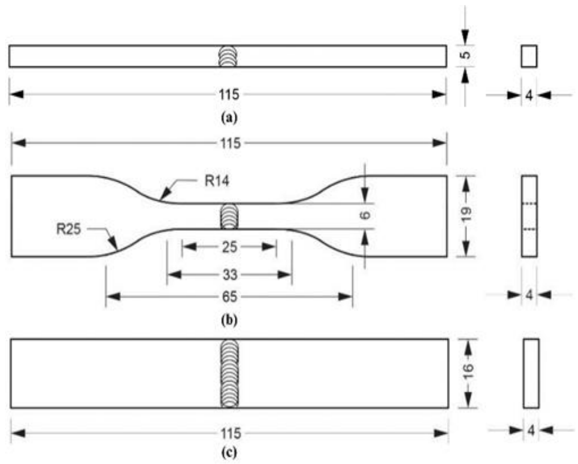

Figure 5. Dimensions (a) hardness test specimen (b) bending test specimen (c) of tensile test specimen

For the mechanical properties of HDPE-PP polymer dissimilar Friction Stir Welding (FSW) joints, a comprehensive evaluation was conducted through a series of mechanical tests and visual analysis, including; ASTM D2240 Durometer Shore-D hardness test, ASTM D638 Type IV tensile test, and D790 Three point bending test. Macro photo visual tests were conducted to observe the joint morphology including joint distribution and pox. specimen dimensions followed the standard configuration shown in Figure 5.

RESULT AND DISCUSSION

The results of HDPE-PP dissimilar polymer Friction Stir Welding (FSW) joint with cylindrical profile pin variation can be seen in Figure 6.

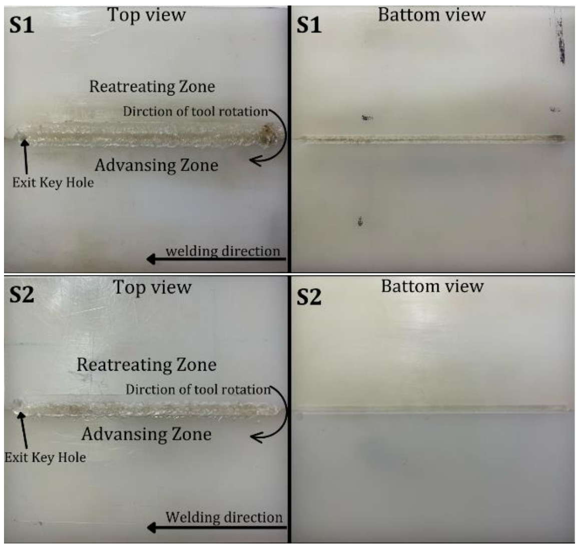

Figure 6. Welding results of welding results of threaded cylindrical profile pin variation profile pin variation

In the Stir Zone (SZ), excessive material stirring causes voids and porosity in the nugget zone [30]. The joint structure becomes less dense due to unstable heat transfer. On the Advancing Side (AS), there is too much friction between the profile pin and the material, which causes overheating. In the Retreating Side (RS), the material flow tends to be more stable because the rotation direction of the profile pin favours void filling, but the surface remains non-uniform [31].

Macro photographs of HDPE-PP dissimilar FSW joints with variation of threaded cylindrical profile pins The results are shown in Figure 7.

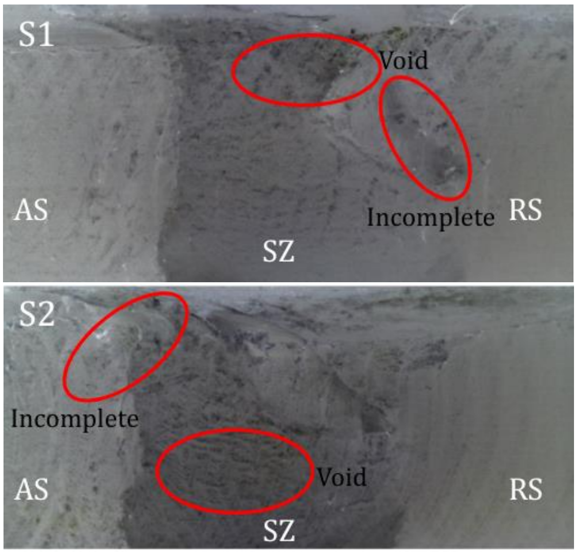

Figure 7. Macro photo of welding results of threaded cylindrical profile pin variation profile pin variation

The observation shows that the lack of agitation causes the HDPE and PP materials to be unevenly mixed. In addition, the uncontrolled temperature during the welding process limits the forging operation of the tool, which causes the continuity of the bond between materials to be broken [32]. As a result, there are more defects in the joint area.

During the welding process, pressure variation occurs at the triangular profile pin, which causes different material flow at the HDPE-PP joint. The nuggets are loaded with sufficient charge, and the pressure is unbalanced, causing the Stir Zone (SZ) area to become brittle [27]. Caused by the uneven stirring effect produced by the triangular profile pin design, the Advansing Side (AS) area shows signs of material piling-up [33]. The Retreating Side (RS) area fills the material better than the Advansing Side (AS), but there is a rough texture. The welding result is shown In figure 8.

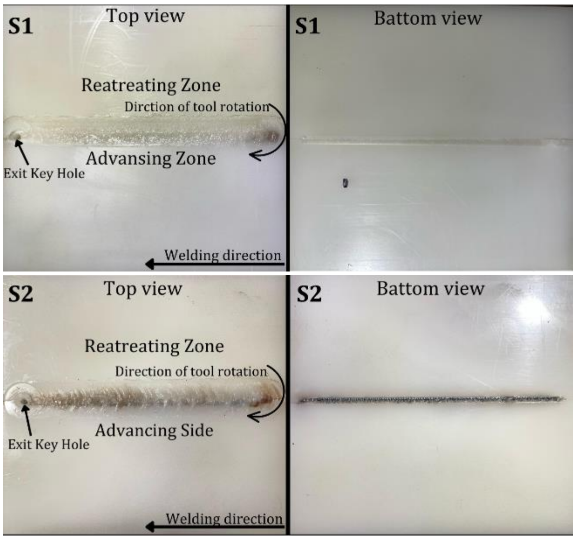

Figure 8. Welding results of triangular profile pin variation

Based on the macro photo observation of HDPE-PP dissimilar joint with variation of triangular profile pin, it is shown in Figure 9. The triangular profile pin increases the material and heat rate in the stir zone area, which can cause internal voids [28]. Due to the difference in melt viscosity between the two materials as well as the uncontrolled temperature gradient. The difference in thermal properties of HDPE and PP, resulting in unbalanced melt fluidity [27]. uncontrolled temperature results in incomplete mixture defects.

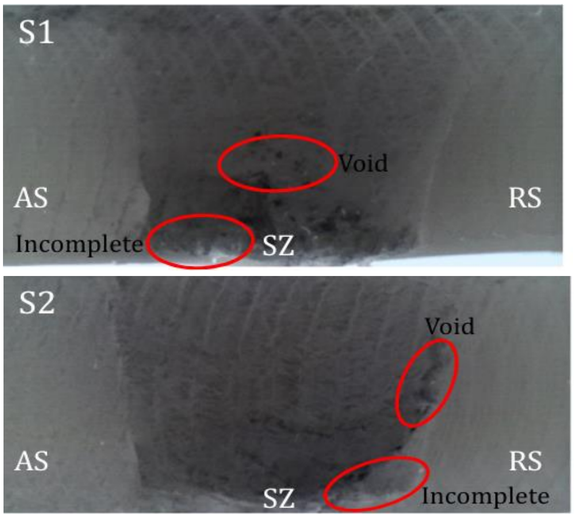

Figure 9. Macro photo of triangular profile pin variation

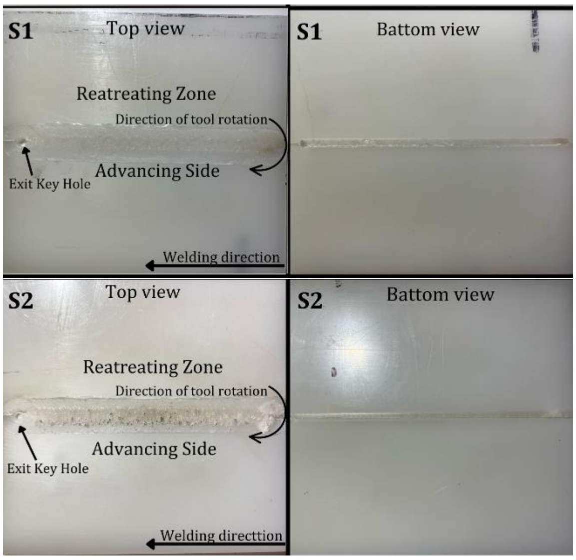

Figure 10. Welding results of grooved tapered cylinderical profile pin variation

HDPE-PP dissimilar polymer Friction Stir Welding (FSW) joints on groove tapered cylindrical pin profiles as shown in Figure 10. The Stir Zone (SZ) area is denser and more solid, and the grooves on the pin profiles promote optimal material flow, preventing voids in the joint. Since the design of the profile pin supports material flow during the welding process, the material flow on the Advancing Side (AS) is well distributed [23], [34]. In the retreating side (RS) area, the best heat control can be seen with almost no visual defects .

Figure 11 shows a macro photo of the groove cylindrical pin profile variation. The Advancing Side (AS) area receives greater frictional energy (forward direction of rotation), resulting in stronger mortar and thermals.

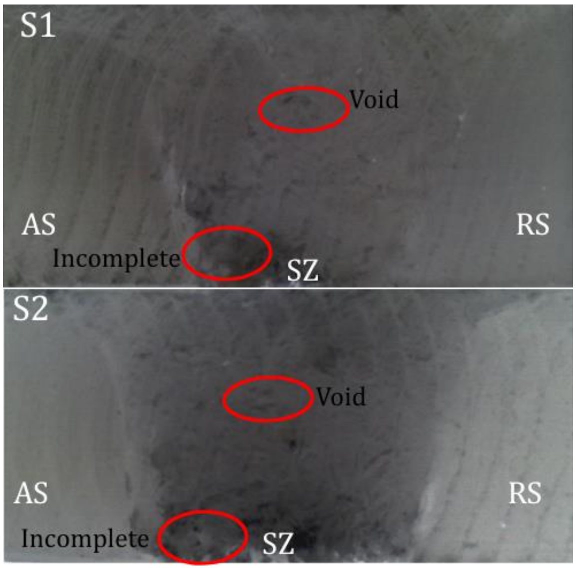

Figure 11. Macro photo of variation of grooved tapered cylinderical profile pin groove

The Retreating Side (RS) area receives relatively lower frictional energy than the Advancing Side (AS) . This difference may lead to differences in microstructure between AS and RS. The Stir Zone (SZ) area is subjected to intense mechanical heating and stirring, which causes the weld area to look dark in some areas of the weld joint. The intense material stirring process causes the SZ structure to become dense and fused.

Table 3. Temperature measurement of FSW process

Profil pin variation		**Starting**	**Centre**	**Final**
Threaded Cylindrical	1	45°C	75°C	82°C
	2	40°C	70°C	72°C
Triangular	1	70°C	80°C	85°C
	2	70°C	80°C	78°C
Grooved Tapered Cylinderical	1	70°C	85°C	93°C
	2	70°C	97°C	99°C

Table 3 shows the results of temperature measurements for each area, namely at the initial, middle and final temperatures in the HDPE-PP Friction Stir Welding (FSW) process. During the welding process, the temperature of each specimen is measured using a thermogun at the initial temperature, middle temperature and at the final temperature during the welding process. One of the purposes of this measurement is to determine changes in material temperature.

When compared to the triangular and threaded cylindrical pin profile variations, the groove tapered pin profile variation showed fewer defects in the HDPE-PP polymer dissimilar FSW welding joints. Due to the more even plasticisation and material mixing between HDPE-PP, the groove tapered cylinder profile pin variation shows fewer defects [28]. During the FSW welding process, the quality, microstructure, and mechanical properties of the joint are affected by temperature control. Therefore, it is important to select the right shape and geometry of the profile pin as it affects the heat distribution during the FSW welding process [29].

Table 4. Area average of hardness values

Profil pin variation	**Advansing side (AS) SHD**	**Stir zone (SZ) SHD**	**Retreating side (RS)**
Threaded Cylindrical	63.5	63	61.5
Triangular	63	61	62,3
Grooved Tapered Cylinderical	62	62.3	60.5
Raw material PP	72.3	71.8	71.5
Raw material HDPE	58.8	58	58.5

The results of hardness testing that has been carried out using a shore-D durometer on HDPE-PP joints using variations of screw cylinder, triangle and groove cylinder profile pins can be seen in Table 4. The test results show that the advancing side area has a higher hardness value, followed by the stir zone and retreating side. Figure 12 shows the average hardness value of each profile pin variation, indicating that the profile pin geometry affects the hardness value of the joint surface. The grooved cylindrical profile pin has the highest hardness value of 62.7 SHD, followed by the triangular profile pin 62.1 SHD, and the threaded cylindrical profile pin with the lowest hardness value of 61.6 SHD. This difference is due to the different pin geometry in controlling material flow and heat distribution during the welding process [34].

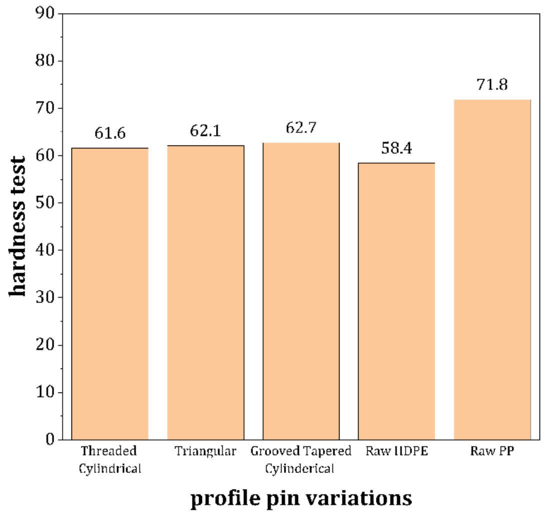

Figure 12. Average value of hardness testing

Factors that affect the hardness of Friction Stir Welding (FSW) joints include; welding parameters, material type, pin profile shape, and heat distribution during the process. [10]. Thermoplastic polymers such as HDPE and PP, are sensitive to temperature increases. When the temperature exceeds the material threshold during the FSW welding process, the material experiences excessive melting, this causes the softened material to tend to be pushed out of the weld zone, potentially causing weld root defects [35].

The shape and geometry of the profile pin greatly affects the heat distribution and material flow during the FSW process. Pin shapes with more angles produce higher temperatures as well as profile pin shapes with sharper angles, causing over-stirring, potentially causing internal voids and reducing joint hardness [33].

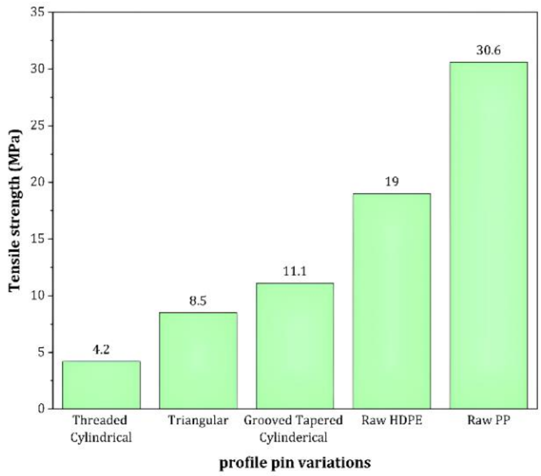

Figure 13. Average value of tensile testing

Based on the bar chart on the tensile test shown in Figure 13. The highest tensile stress value is obtained in PP raw material specimens with an average value of 30.6 MPa followed by HDPE raw material with an average value of 19 MPa. Meanwhile, in the welding connection of the pin profile variation, the highest average value of tensile loading of 11.1 is obtained in the variation of the groove tapered cylindrical profile pin. Followed by the triangular profile pin variation with an average value of tensile loading of 8.5 MPa. Meanwhile, the lowest average value of tensile loading is obtained in the variation of threaded cylindrical profile pins at 4.2 MPa.

The grooved tapered cylindrical profile pin provides more even material flow and more stable shear force than other profile pin variations, it can be seen in Figure 11 that the macro photo results on the grooved tapered cylindrical profile pin variation have few defects. The sharper angle on the triangular profile pin creates turbulent flow in the stir zone due to greater deformation, this causes overheating, changes in material structure and potentially creates internal voids [1][36]. Figure 9 shows the presence of internal cavity defects that cause the average value of tensile loading to be lower than the groove tapered cylindrical profile pin but higher than the threaded cylindrical profile pin, seen in Figure 7 there are void defects at the base of the weld zone due to inhomogeneous material flow.

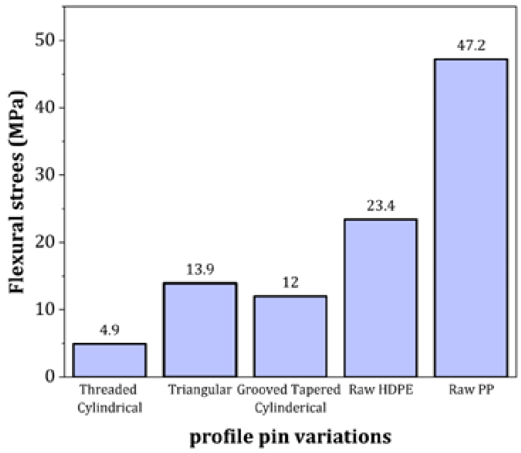

Figure 14. Average value of flexural testing

The flexural test results in Figure 14 show that the highest average value is obtained in PP raw material of 47.2 MPa, then the average value of 23.4 MPa is obtained in HDPE raw material. Meanwhile, in HDPE-PP polymer dissimilar FSW joints with variations in pin profile, the highest average value was obtained at a triangular pin profile of 13.9. The average value of 12 MPa or obtained on the groove tapered cylindrical profile pin. While the lowest flequral test average value of 4.9 MPa in the variation of threaded cylindrical profile pins.

The difference in bending strength values in this study is due to welding defects in the stir zone area so that stress transfer is not optimal. where the bending strength value achieved in welding depends on the number of defects and the size of the weld defect [29], [37][38].

This phenomenon is related to the bending stress condition, which triggers the propagation of the crack path away from the fracture plane in the welded joint. The results showed that most of the crack initiation originated from shrinkage voids formed during the cooling stage in the stir zone (SZ) [39]. This finding indicates a direct relationship between crack branch propagation and the presence of shrinkage voids that serve as the main source of cracks.

CONCLUSION

Based on the research results, it can be concluded that the shape of the welding profile pin has a significant influence on the quality of the joint resulting from the Friction Stir Welding (FSW) process on high density polyethylene (HDPE) - polypropylene (PP) material. Different rheological properties of polymers, especially melt viscosity, cause different material flow behaviour during Friction Stir Welding (FSW) process.

Shape and geometry are responsible for generating heat and controlling material flow during the FSW process. The shape and mechanical properties of the joint are directly affected by these factors. The grooved tapered cylinder pin obtained an average tensile strength of 11.1 MPa, followed by the triangular pin at 8.5 MPa and the threaded cylinder at a lower value of 4.2 MPa. The triangular pin reached 13.9 MPa, higher than the grooved tapered cylinder (12 MPa) and threaded cylinder (4.9 MPa). The grooved tapered cylinder pins had an average hardness of 62.1 SHD, slightly higher than the threaded (61.6 SHD) and triangular (6.7 SHD) cylinders. The grooved tapered cylindrical pins showed a dense stir zone (SZ) with minimal voids, while the triangular and threaded cylindrical pins had porosity and rough texture in the RS/AS. These results are in line with tensile and flexural tests, where material density correlates with mechanical strength.

The choice of pin geometry largely determines the quality of HDPE-PP FSW joints. Grooved tapered cylindrical pins are optimal for applications that prioritise tensile strength and density, while triangular pins are suitable for bending loads. Hardness test results and macro photographs reinforce that controlled material flow (from pin design) reduces internal defects, which is reflected in the final mechanical performance.

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