SEMESTA TEKNIKA
E-ISSN: 2502 - 5481 P-ISSN: 1411 - 061X

Semesta Teknika
Vol. 27, No. 1, 66-80, Mei 2024
DOI: https://doi.org/10.18196/st.v27i1.22182

The Effect of Tool Rotational Speed and Welding Configuration on the Mechanical Properties of High Density Polyethylene (HDPE) Plate Friction Stir Welded Joint

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Keywords:
Friction stir welding; HDPE, double side welding; tensile strength; flexure strength

Abstract
The study investigates the impact of tool rotational speed and welding configuration on the mechanical properties of friction stir welded joints of HDPE plates. The plates were cut into rectangular shapes and clamped on a metal plate for FSW welding. Two welding configurations were used: single-side welding (SS) and double-side welding (DS), with rotational speeds of 900, 1500, and 2000 rpm. The plates were subjected to tensile and bending tests, and angular distortion was also measured. The findings suggest that decreasing the tool's rotational speed to 900 rpm and using double-side welding reduces angular distortion and improves tensile and flexural strength. The study emphasizes the importance of defect reduction techniques in improving the mechanical properties of HDPE FSW joints.

INTRODUCTION

In last decades, there has been a widespread use of lightweight materials in the transportation industry with the aim of minimizing greenhouse gas emissions (Lyu & Choi, 2015). Plastic materials, known for their low density, moldability, corrosion resistance, and low production costs, have become the preferred material in various industries, particularly in automobile, naval, and aerospace sectors (D. Mishra, *et al.*, 2019). Among the others polyethylene is the most extensively utilized plastic globally in terms of volume. It has exceptional properties including high toughness, resistance to abrasion and impact, minimal water absorption, affordability, and the capacity to be recycled. This material is extensively employed in the fields of agro-industry, medicine, and household applications (Raouache *et al.*, 2018). However, the use of joining technologies is frequently necessary for components made of plastic material that have a vast scale and complex shape. Conventional methods for combining plastic materials include mechanical joining and adhesive bonding. Furthermore, plastic materials can be joined using welding techniques which are can be divided into three chategories: chemical joining techniques, mechanical joining techniques, and thermal joining techniques (Karpat & Kucukoglu, 2017). However, both mechanical joining and adhesive bonding have drawbacks in terms of productivity and recyclability, as they require additional machining processes or time for joining. On the other hand, fusion welding has low productivity, due to the welding technique taking a significant amount of time to complete. In addition, welding also presents a difficulty as it is prone to thermal damage, which is often caused by excessive heating during the procedure. Hence, it is necessary to combine technology with elevated efficiency and dependability while working with plastic materials. Utilizing Friction Stir Welding (FSW) for joining plastics is the optimum solution to accelerate the welding process, enhance productivity, and lower manufacturing expenses.

FSW is a developed method of connecting solid materials without melting them (Mishra & Ma, 2005). The invention of this technique took place at The Welding Institute (TWI) in the UK in 1991. Initially, it was mostly used for aluminum alloys (Tiwari *et al.*, 2013) and it was applied first on polymers in 1991 (Strand, 2003). FSW has the potential to create steel joints with exceptional hardness and strength, and to carry out weldments with great efficiency in comparison to fusion welding (Liu, *et al*, 2018). However, FSW and other welding methods cannot be applied on all types of polymers because thermosetting polymers alter their molecular structure irreversibly at high temperatures, even below the melting point. In contrast, thermoplastic polymers soften without degrading their molecular structures when heated. They are recyclable polymers because they can be remoulded. Therefore, FSW only applies to thermoplastics (Stokes, 1989). This method has successfully joined ABS (Mendes, *et al*, 2014), PA6 (Husain *et al*., 2015), polycarbonate (PC) (Lambiase, *et al*., 2020), polyethylene (PE) (Bozkurt, 2012), PLA (Derazkola & Simchi, 2018; Sharma *et al*, 2020), PMMA (Derazkola & Simchi, 2018), polypropylene (PP) (Moochani *et al*, 2019), and polyvinyl carbonate (PVC) (Inaniwa *et al.*, 2013).

The primary variables include rotational speed, welding speed (or traverse speed), tilt angle (or attack angle), axial force, and plunge depth (or penetration depth) (Pereira *et al*.,2021). The conventional tool for welding involves a shoulder and pin rotating together, generating heat to heat and soften the material. The pin mixes the softened material in the weld seam, while the shoulder prevents material projection out of the welding zone. FSW, is environmentally friendly and does not require filler material, a protective atmosphere, or joint preparation (Payganeh *et al.*, 2011). It is economically and energy-efficient due to the friction between the base material and the tool, beyond the energy of plastic deformation. Butt and lap joint configurations are the most common in FSW.

The low thermal conductivity of thermoplastics can lead to root defects in the gap between the pin and supporting plate during FSW. This is due to the hindered heat dissipation in the stir zone, restricting plasticity and causing the polymer to fracture due to the high share force exerted by the rotating tool. This phenomenon is common in FSW of thermoplastic. To address this issue, a few researchers applied double side FSW on joint strength. Saeedy and Givi (2010) studied the effect of double-side FSW for HDPE sheets. Two tools with distinct geometries, including differences in the length and diameter of the pin, as well as the diameter of the shoulder, are utilized for each specific type of welding. It was found that the tensile and impact strength of double-sided weld was greater than that of single-sided weld. Arici and Sinmaz (2005) adopted a double pass approach for FSW of 5-mm MDPE plates, using a tool with a pin height of approximately half of the plates. By employing dual passes of the tool on the FSW of PE, they successfully eradicated the root fault, which plays a crucial role in initiating failure in the welding area, and obtained favorable tensile and bending outcomes.

Nath *et al.*(2021) presents a novel approach for friction stir welding of PP using a double-side welding technique. It examines the impact of tool rotational speed on joint construction and properties, compares torque and forces during double-side welding with single-side welding, and reveals defect-free sound welding with uniform material flow. The study also examines molecular bonds and finds that double-side welding yields superior tensile and flexural strength joints compared to single-side welding. In addition, Azhiri *et al.* (2019) stated that an increase in the number of passes results in a substantial decrease in angular distortion. On the other hand, they said that increasing the tool rotation and decreasing the travel speed led to a significant increase in heat input, which in turn enhances the stirring action. Consequently, both the tensile and impact strengths are enhanced. Nevertheless, the thermal energy leads to an increase in the joint's ability to be formed and results in a high level of residual stress, which in turn causes an increase in angular distortion impacting the mechanical properties and performance of the final product.

In this experimental study, the double-side welding technique was applied to increase the quality of the FSW-ed HDPE joint. At various tool rotation speeds, and different tool geometry for double side FSW, the mechanical characteristics of the samples welded using single- and double-side procedures have been compared to one another. An analysis is conducted on their impact on the weld joint strength.

RESEARCH METHODS

In this research, HDPE plates with a thickness of 5 mm (Figure 1a) were cut into rectangular shape in sizes of 80 mm wide and of 100 mm long using a laser cutting machine, as many as two. Both are then placed on flat metal plate and clamped with a vice to avoid separation in the butt-joint position for FSW welding to be carried out. Both FSW tool from heat-treated ST 37 steel was fabricated (Figure 1b), including a shoulder diameter of 16 mm, with a pin diameter of 3 mm and without the pin. The pins had a right-hand thread with a pitch length of 1 mm. A tool with a pin length of 4.5 mm was utilized. The experimental setup of the FSW machine is shown in Figure 1.c. The FSW welding process uses a vertical milling machine model FM-2SK Chevalier. This machine features dynamically balanced drives and pulleys and has 3 axes: 400 mm for the Y axis, 370 mm for the Z axis, and 901 mm for the X axis.

The present investigation utilized two distinct welding procedures. There are two types of welding: single-side welding (SS) and double-side welding (DS). Tool I was used to weld all single-side welding. In double-side welding, the welded material is typically cooled to room temperature after welding on the first side (DS1) using Tool A before proceeding with welding on the other side (DS2) applying Tool II. Welding parameters such as welding speed at 5 mm/minute and plunge depth of 0.5 mm were maintained constant. In contrast, the rotational speed varied from 900 rpm to 1500 rpm and 2000 rpm. Inaniwa *et al*. (2013) have suggested applying transverse speed in the range of 5-50 mm/min, with a rotation speed of 800-1200 rpm for an FSW on an HDPE plate.

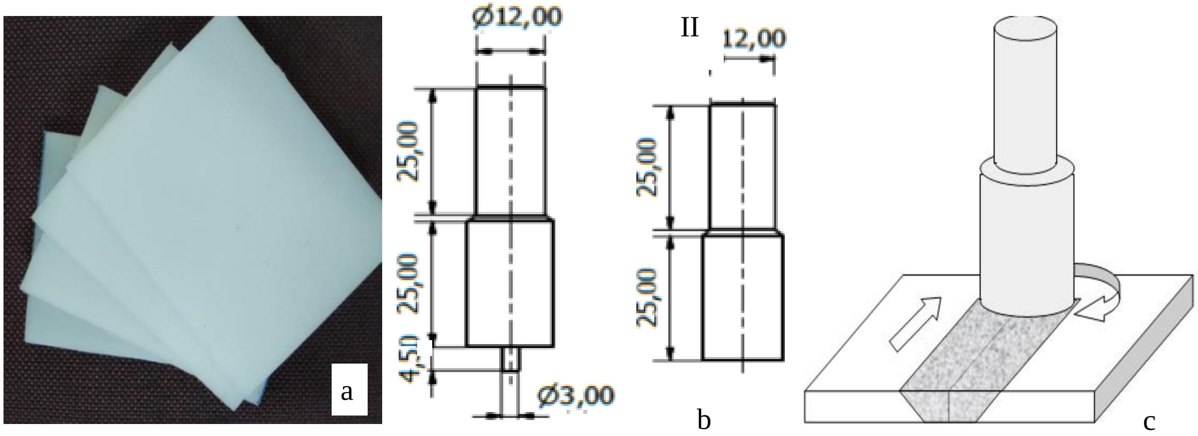
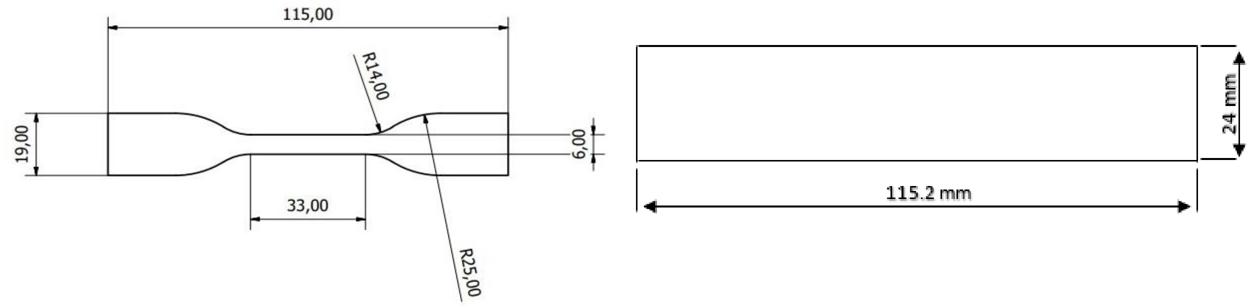


Figure 1 (a) HDPE Plates, (b) The two FSW tool geometry, (c) Schematic of FSW processes.

After welding, the resulting joined HDPE plate is cut using a laser cutting machine into specimens for tensile and bending tests per ASTM D638 Type IV (Figure 2.a) and ASTM D790. Each test was replicated three times at each level. Angular distortion was measured using the image analysis software Image.



a b

Figure 2. (a) Tensile test specimen ASTM D638 type IV, (b) bending test spesimen ASTM D79-0

Observations were made on the results of welded joints, both one pass and two passes, and compared. Tensile and bending testing was carried out using a Zwick/Roell Z020 brand universal tensile testing machine made in Germany. The tensile test specimen is placed in a suitable chuck and then loaded with a sliding loading speed of 1 mm/minute until it breaks (Figure 3.a). The bending test was carried out using the three-point bending method by placing the bending specimen on a support with a span distance of 80 mm and then applying a loading speed of 2 mm/minute (Figure 3.b). The fracture results of both the tensile test and bending test were observed macroscopically.

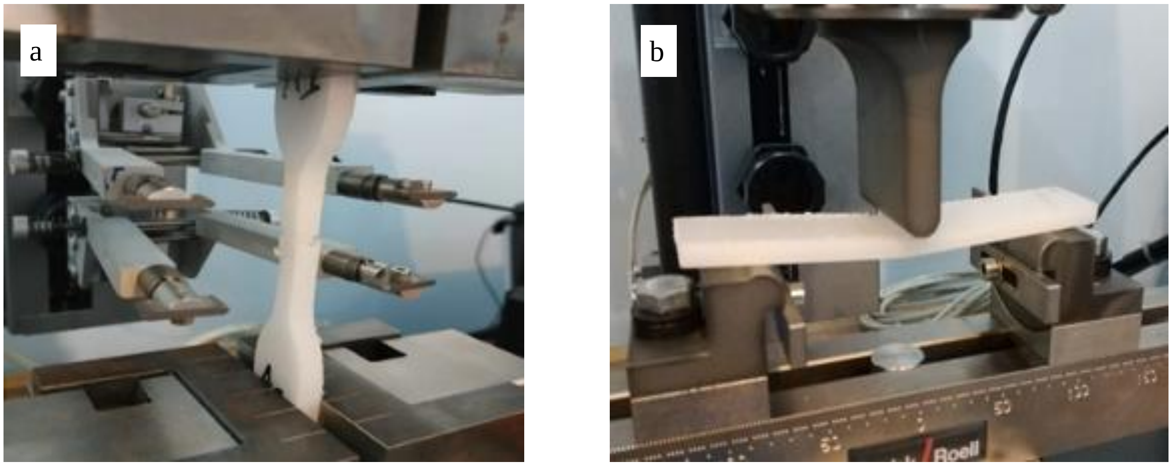


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Figure 3. (a) Tensile testing (b) bending testing using a Zwick/Roell Z020 testing machine

RESULTS AND DISCUSSION

HDPE plate FSW-ed Joint

FSW is a welding technique that uses frictional heat generation and mechanical stirring to join two materials. The rotating tool generates frictional heat, softening the material without reaching its melting point. The softened material around the tool undergoes plastic deformation and is stirred by the rotation, effectively mixing the material from both sides of the joint. The shoulder tool prevents material from protruding and promotes smooth material flow along the joint line. This mechanical action creates a bond as the material cools and consolidates. FSW involves two sides of the weld joint, the advancing side, and the retreating side (Figure 4. Top). The advancing side is where the FSW tool moves forward, pushing material ahead, and resulting in plasticized material. This side experiences higher temperatures and greater plastic deformation, leading to better weld quality and mechanical properties. At higher tool rotation speed, the plasticized material is expelled to the retreating side resulting in more flash observed in the area. The retreating side, opposite to the tool's direction, pulls the material back, resulting in less plastic deformation. This side experiences lower temperatures and less plastic deformation, causing differences in microstructure and mechanical properties compared to the advancing side (Ahmad, *et al*.,2023; Mishra & Ma, 2005). The weld surface is categorized as a poor surface (Pereira *et al*., 2021). Poor surface finish in welding refers to the undesirable appearance or texture of a welded joint. Common characteristics include roughness, waviness, porosity, and scatter. Figure 7. bottom, reveals that double-side pass welding successfully eliminates root defects (Nath *et al*., 2021) and increases joint efficiency but leaves a poor surface finish on the bottom surface.

Root defects were observed in every single side weld produced in this study (Figure 7. middle). A root defect is a non-welded area at the bottom of the joint. Because the welds were completed with a gap between the pin and the anvil, and the thermoplastic's inadequate thermal conductivity, the bottom of each joint was left unwelded. In most cases, a little amount of molten material was extruded into this gap to assist connect the workpieces, but the extrusion weld was much weaker than the FSW zone resulting brittle failure (Strand, 2004).

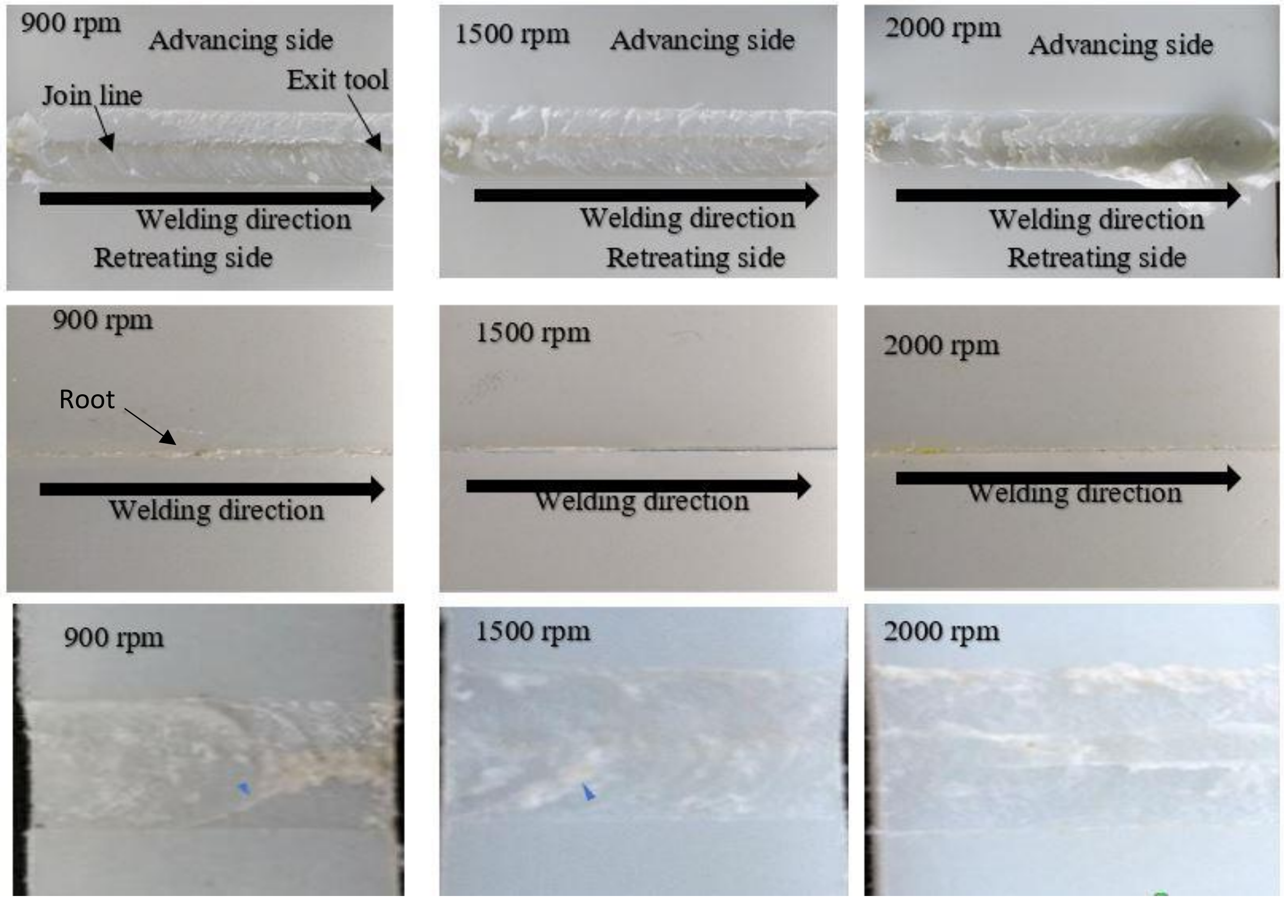

Figure 4. FSW welding results for welding on one side, weld surface (top), bottom weld surface (middle), and bottom weld surface after double side welding (bottom)

After the FSW welding process, the specimen was removed from the clamping and then the angular distortion that occurred was observed using the open-source image analysis software ImageJ. In single-side welding at tool rotation speeds of 900 rpm and 2000 rpm (Figure 5. a and c), angular distortion of around 3.35^o and 3.5^o (Figure 5. b and d) were observed, respectively. Meanwhile, in double-side welding, it was observed that it decreased to 2.3o and 2.9o, respectively. During single-side welding, heat is primarily applied to one side of the joint, causing uneven temperature distribution and thermal gradients. Material flow is more pronounced on the heat-applied side, introducing asymmetrical stresses. Residual stresses form due to non-uniform cooling and solidification of the material. Joint misalignment increases the risk of angular distortion.

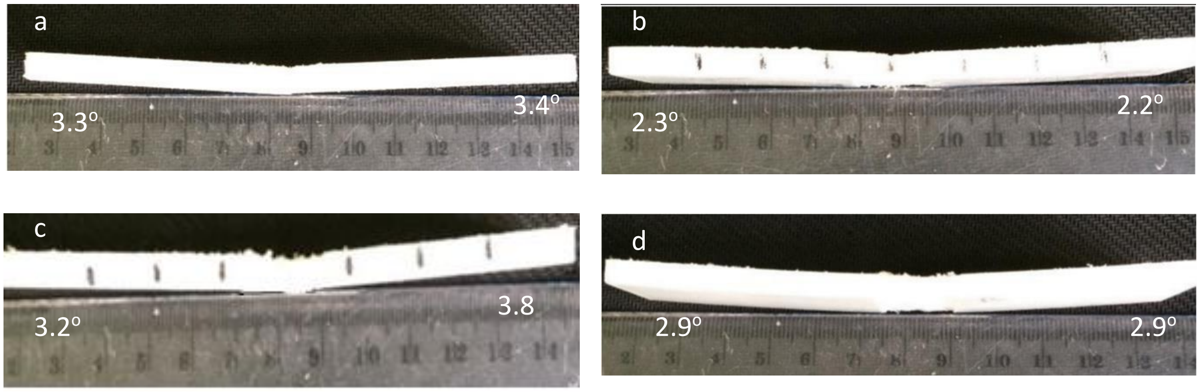

Figure 5. Angular distortion of FSW joint with single side welding at (a) 900rpm, (c) 2000 rpm, double side welding at (b) 900 rpm, (d) 2000 rpm

In contrast, double-sided welding in FSW of HDPE plates can reduce angular distortion. It promotes symmetrical heat distribution, minimizing temperature gradients across the welded joint. It also promotes balanced material flow, creating a more uniform material displacement and consolidation, which mitigates internal stresses within the HDPE material. It also reduces residual stress, as the cooling rates from both sides are more uniform, resulting in lower residual stresses and reduced angular distortion. Azhiri *et al*., (2019) discovered that the volume percentage, pass number, and tool rotation have an impact on both the energy of impact and the angular distortion. With continued thermomechanical loading, the material in the FSP region undergoes degradation, resulting in a loss in both strength and impact energy. However, an increase in the number of passes results in a substantial decrease in angular distortion. It is also revealed that increasing the tool rotation and decreasing the travel speed led to a suitable heat input and enhance the stirring action. Consequently, the tensile and impact strengths are enhanced. Nevertheless, the thermal energy leads to an augmentation in the joint's ability to be shaped, as well as a significant rise in the residual stress, which in turn amplifies the angular distortion.

Tensile Testing Result

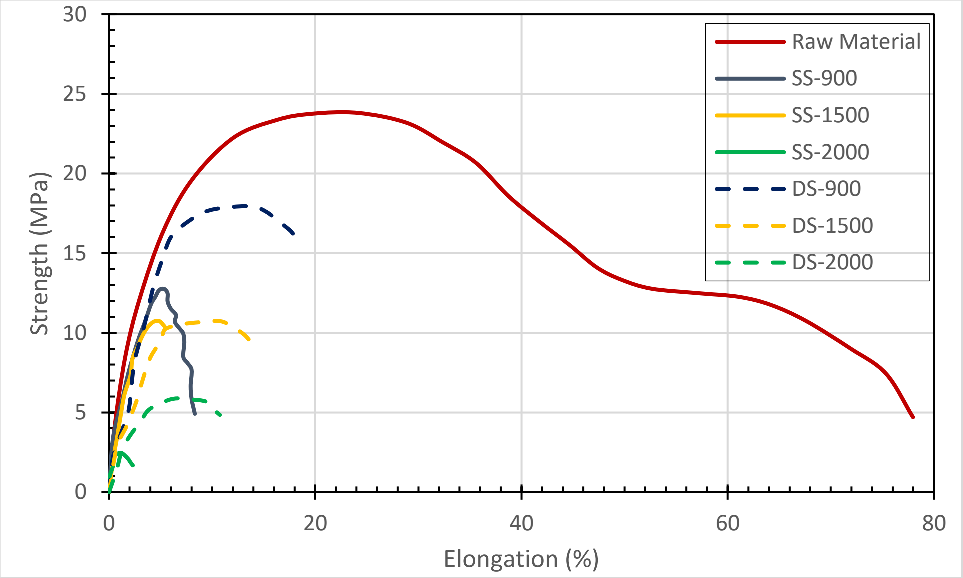

Figure 6. Stress-strain curved of the of the welded joint at various processing parameter compared to raw material

Tensile testing has been conducted on several components, including raw materials, and friction stir welded (FSW) joints with single-side and double-side passes. By examining the strain-stress curve (Figure 6), we may analyse many tensile characteristics of the material, such as tensile strength, strain, modulus of elasticity, and yield strength. The red curve represents the HDPE raw material, which has a characteristic tensile behaviour commonly observed in polymeric materials, with a significant plastic area and a very high strain (Amjadi & Fatemi, 2020). However, except for the double-side specimens (blue-yellow-green dash curves in Figure 6), all welded joints exhibited minimal strain and brittle fracture (blue-yellow-green curves in Figure 6).

Friction stir welding (FSW) can cause alterations in the microstructure of high-density polyethylene (HDPE), resulting in a more intricate welding structure in the area where the welding takes place. it may also reduce its ductility, so increasing its susceptibility to brittle fracture. Strand (2004) determined that the brittle failure of the specimen during tensile stress tests is caused by root defects located at the bottom of the welds. These defects occur in the region of the weld nugget where proper stirring is not achieved, resulting in incomplete welding which led to brittle fractures when subjected to tensile loading. Regarding this, double-sided FSW is carried out. It is a process that involves passing a tool through both sides of a joint, resulting in improved material mixing and bonding, reduced residual stresses, optimized material flow, enhanced heat dissipation, and increased processing parameter control. This results in a more homogeneous microstructure, reduced defects, and better distribution of stress and strain, leading to improved strength and ductility. Additionally, it helps to reduce residual stresses, optimize material flow, and control processing parameters, resulting in a more desirable balance between material softening and flow, resulting in improved joint properties, compared to single-sided FSW (Arici & Sinmaz, 2005).

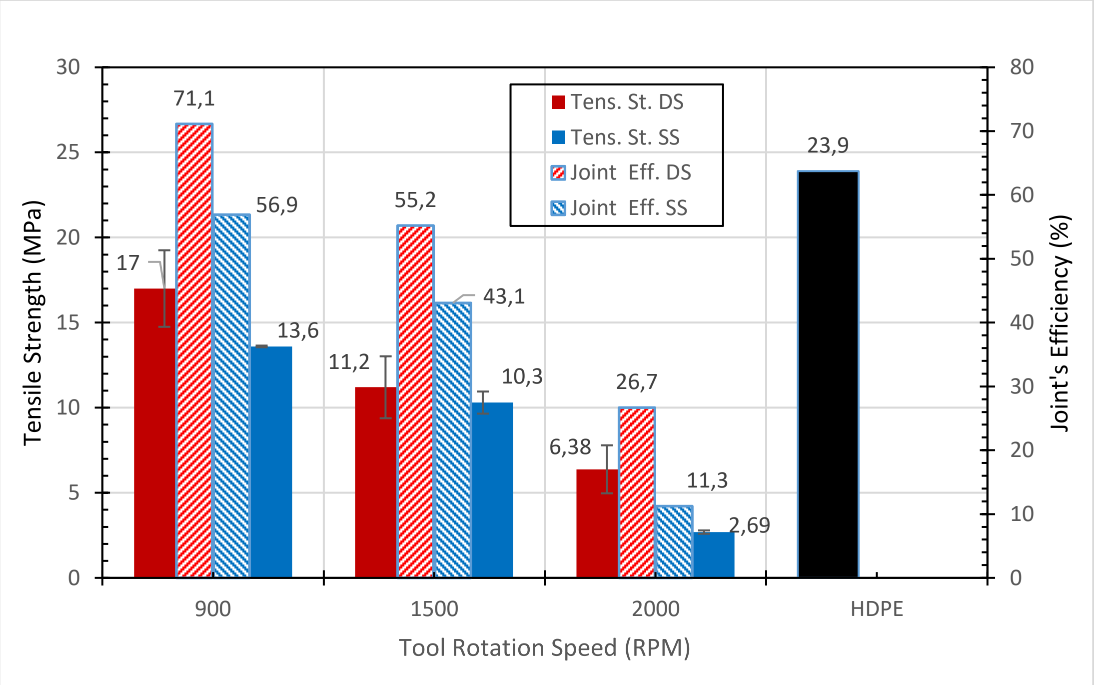

Figure 7. Tensile strength of HDPE and joint's efficiency of FSW plate joint at various tool rotational speed and welding configuration (double-side, single-side)

HDPE is a widely utilized thermoplastic material renowned for its mechanical characteristics, particularly its tensile strength. The tensile strength of HDPE is subject to variation based on characteristics such as molecular weight, crystallinity, production conditions, and additives. The normal range for the tensile strength of HDPE is between 21.4MPa and 33 MPa (Matweb, 2024). The tensile test result of 23.8 MPa achieved in this study (Figure 7) closely corresponds to the findings published in previous research, where the tensile strength was determined at 22.5 MPa (Bozkurt, 2012). The close similarity in values indicates that the material's mechanical properties have been consistently and reliably characterized in many studies. The conformity of the raw material to specification standards, as demonstrated by the outcomes of the tensile testing, offers a basic benchmark for its mechanical behaviour and performance characteristics.

The strength of FSW joints by single-side welding passed were found decrease as the rotation speed increases. The study reveals that FSW with two passes and a single pass at different rotation speeds significantly impacts the strength and quality of welded joints. At 2000 rpm, the joint efficiency is 26.7%, suggesting a lower strength compared to the base material due to excessive heat input. However, at 1500 rpm, it increases to 55%, representing better strength due to reduced heat input and improved material flow. It increases to 71%, at 900 rpm, demonstrating a significant enhancement in joint strength. For a single pass, it has a lower efficiency of 11.3% at 2000 rpm, possibly due to insufficient material mixing and bonding. At 1500 rpm, it improves to 43.3%, exhibiting better material consolidation and joint formation. At 900 rpm, it increases to 56.9%, indicating that optimizing rotation speed is crucial for achieving stronger joints. Those phenomena can be described as follows. Firstly, increased rotation rates result in an augmentation of the heat produced during the welding process. The increased temperature can cause a greater degree of material softening in the vicinity of the weld area, resulting in a decrease in the overall strength of the joint. In addition, the increased rotational speeds can worsen material flaws such as empty spaces and abnormalities in the microstructure, which further weaken the strength of the joint. Moreover, the heightened rotational velocity could potentially impact the grain morphology of the material within the welding region. Intense agitation at elevated velocities may lead to the reduction of grain size, which might influence the mechanical characteristics of the joint, potentially diminishing its strength.

Extensive research investigations have thoroughly examined the impact of rotational speed on the characteristics of FSW joints. An investigation conducted by Mishra and Ma (2005) analysed the impact of process parameters, such as rotation speed, on the microstructure and mechanical characteristics of FSW joints. They revealed a distinct association between the speed of rotation and the strength of the joints, with higher rates often resulting in diminished joint strength. Furthermore, a separate study conducted by Schmidt *et al.* (2003) examined the correlation between the speed of rotation and the quality of joints in aluminum FSW joints. They noticed that when the rotation speed increased, the temperatures at the weld contact also increased, causing the material to become softer and weakening the joint. On the other hand, the double-sided pass technique in FSW has been proven to improve joint quality and mechanical performance. It leads to smaller defect-free joints and higher tensile strength, as per previous research (Arici & Sinmaz, 2005; Nath *et al.*, 2021). This technique improves material consolidation and homogenization across the joint interface, forming a defect-free weld zone with enhanced metallurgical bonding and structural integrity. This results in higher resistance to tensile loading, resulting in higher tensile strength compared to single-pass welds. In addition, the tensile strength of the joint is comparable to the previous research, which is achieving in the range of 70-83% (Abdulrehman & Marhoon, 2023; Bozkurt, 2012; Raouache *et al.*, 2018). However, more scattered results were observed in double-pass FSW joints. It may be due to the increased complexity of the welding process, variations in interpass heat effects, differences in material mixing and homogenization, defects formation and elimination, process parameter optimization, and material response, which are crucial for improving joint consistency and reliability.

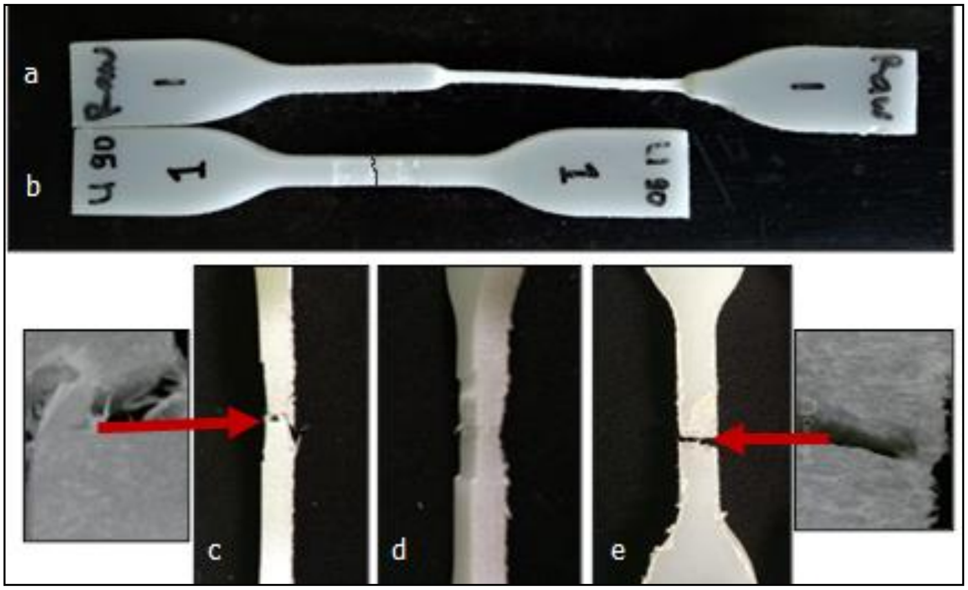

Figure 8. HDPE Tensile tested specimen: a) raw material, b) FSW-ed single side welding pass at 900 rpm, FSW-ed double side welding pass at: c) 900 rpm, d) 1500 rpm, and e) 2000 rpm

Figure 8.a shows that a high strain in the HDPE tensile test specimen reflects the material's ductility by showing it can experience considerable deformation before failing. The stress-strain diagram, as presented in Figure 6, shows that the material exhibits a significant elongation before approaching its breaking point, visually confirming this. The tensile specimen with single-side welding at a tool rotation speed of 2000 rpm was the lowest weld quality. It was very easy to separate the tensile specimen (Figure 8b). The HDPE joint with double side welding pass at 900 rpm weld has a fibrous surface failure (see red arrow in Figure 8c), which indicates that the fracture surface of the material shows a fibrous or fibrous-like appearance, resembling ripped fibers rather than a smooth surface. The fibrous look suggests that the material undergoes plastic deformation before failure. In contrast, at higher toll rotation speeds smoother surface failure were found showing the occurrence of lower plastic deformation (Figure 8d & 8e).

Three Point Bending Test Result

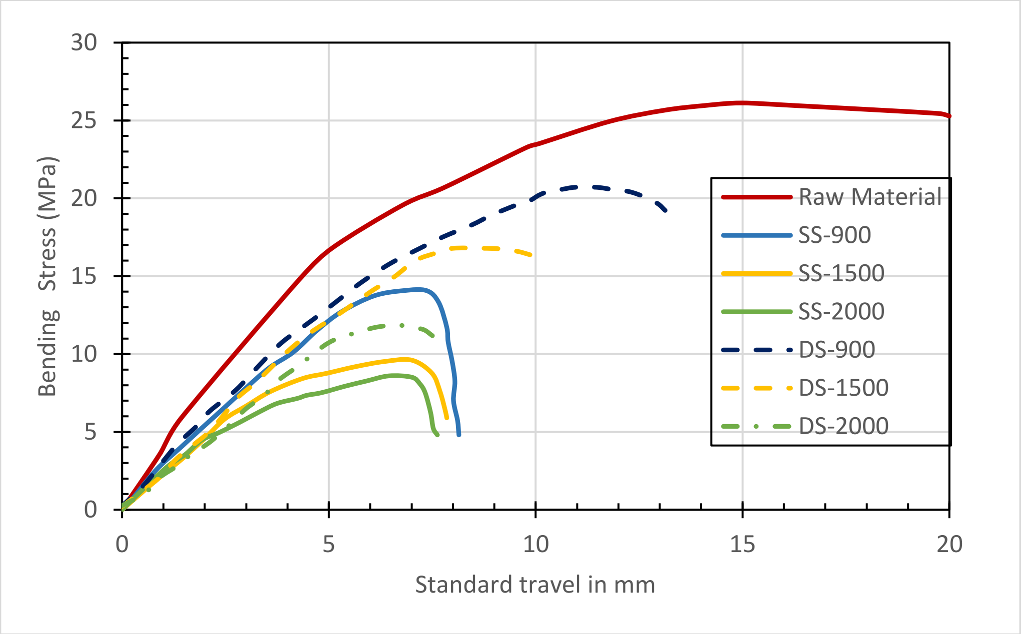

Figure 9. Bending stress-travel diagram of HDPE and FSW plate joint at various tool rotation speed and welding configuration.

The flexural test findings, particularly the flexure-travel diagram, demonstrate the distinctive properties of polymeric materials in relation to flexure strength and compare it to the flexure strength displayed by FSW joints. Polymeric materials commonly display a non-linear stress-strain behaviour when subjected to bending. This behaviour is characterized by an initial elastic phase, followed by plastic deformation and eventual failure (Mirabzadeh & Ehsani, 2021). The flexure-travel diagram graphically illustrates this phenomenon by displaying the exerted force (or flexure) against the corresponding displacement (or travel) of the specimen. For polymeric materials, the diagram may exhibit a progressive rise in flexure strength until reaching up a certain point, followed by a plateau or gradual decrease as the material undergoes plastic deformation (see red curve in Figure 9). The maximum flexural strength is the biggest load that the material can withstand before it fails. The peak strength of a material refers to its capacity to endure bending stresses and resist deformation when subjected to external forces. FSW joints may have distinct flexural strength properties in comparison to polymeric materials, owing to differences in material composition, microstructure, and processing circumstances. The flexure-travel diagram for FSW joints exhibits a nonlinear stress-strain response, which can vary in shape and magnitude according to factors such as welding settings, joint geometry, and material properties.

In the double-pass FSW (see the dash curves in Figure 9), when the shape of the flexure-travel diagram closely resembles that of the raw material, it indicates that the welding process has successfully solidified the joint and reduced the occurrence of flaws. The resemblance in form suggests that the mechanical characteristics of the joint closely mirror those of the raw material, with a steady rise in bending strength followed by a slow decline or stabilization before to failure. This signifies a tightly connected and structurally stable junction, demonstrating the effective merging of the material during the welding procedure (Arici & Sinmaz, 2005). In contrast, the flexure-travel diagram in single-pass FSW has a distinct shape, especially after attaining the peak flexural strength (see the blue, yellow, and green curves in Figure 9). The significant decline in flexural strength after reaching the maximum load indicates the presence of a crucial flaw, such as a root defect, in the joint contact. Root defects may occur due to insufficient material blending or poor tool penetration during the welding process, leading to vulnerable areas that are prone to failure when subjected to bending force (Mishra *et al.*, 2019). The abrupt decline in the ability to resist bending signals a specific failure inside the joint, resulting in early breakage and diminished overall structural strength.

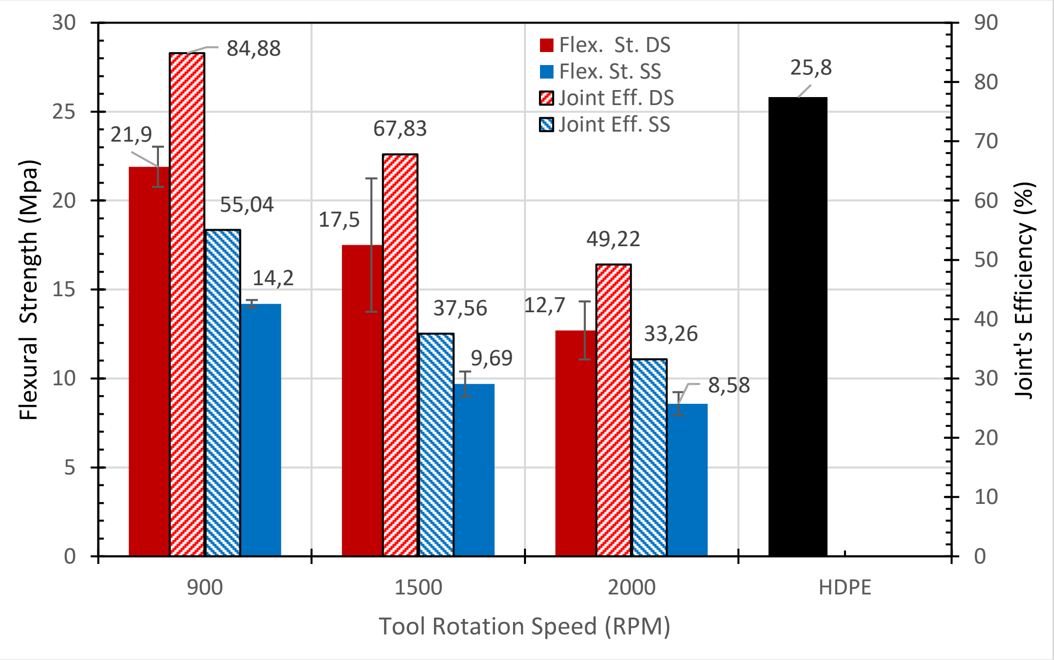

Figure 10. Flexure strength of HDPE and its' efficiency of FSW plate joint at various tool rotation speed and welding pass

Figure 10 shows that the flexure strength of the HDPE plate was found of 25,8 MPa which is comparable to the commercially available HDPE and previous research (Azarsa & Mostafapour, 2014; Mitsuboshi, 2021), However, FSW joints were lower than that of the HDPE plate indicating the welding process causes defects, alterations in the microstructure, or areas of weakness inside the joint. FSW joints exhibit a decrease in flexural strength with an increase in rotational speed, a trend that mirrors tensile strength. This is due to increased frictional heating at the weld interface, leading to excessive material softening, defects, and irregular grain growth. Higher rotational speeds result in lower flexural strength, reflecting the adverse effects of excessive heat input. Double-pass FSW yields higher flexural strength reaching joint's efficiency up to 85% compared to single-pass FSW which only achieving that of 55%, as it involves additional welding passes for material consolidation, defect mitigation, and refinement of the joint microstructure. Previous research reported flexural strength of FSW with optimized welding parameters in the range of 69-95% (Azarsa & Mostafapour, 2014).

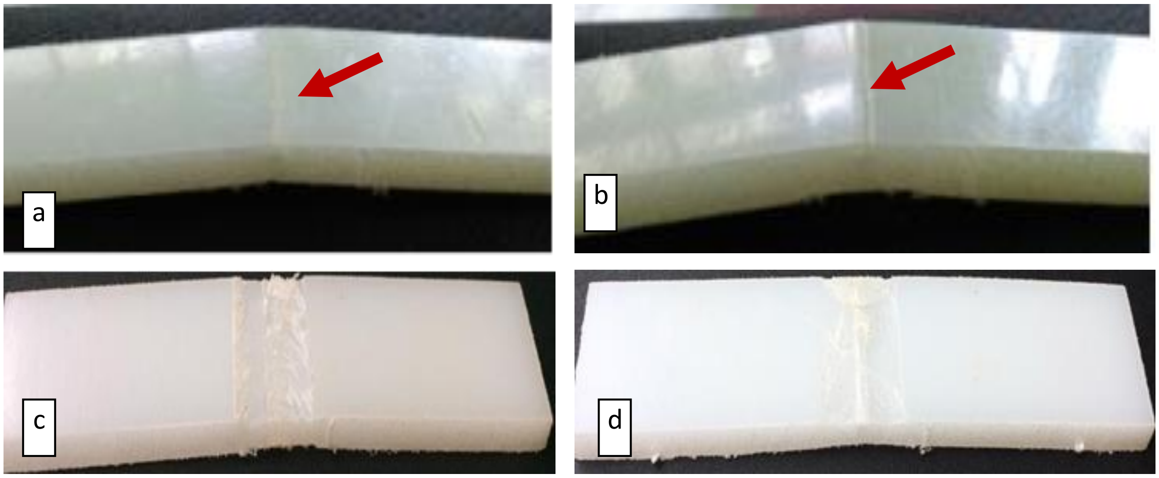

Figure 11. Three-point bending specimen's failures, single-side welding at (a) 900 rpm, (b) 2000 rpm, double side welding at (c) 900 rpm, (d) 2000 rpm.

The three-point bending test yielded significant information regarding the behaviour of single-side and double-side welded joints when subjected to stress. Single-side welding was found to be prone to crack initiation at root defect (see red arrow in the Figure 11a and 11b). Similar finding regarding the occurrence of the cracks were also found by (Arici & Sinmaz, 2005), but double-side welding showed resilience and provided improved resistance to early failure (Figure 11c and 11d). These findings emphasized the significance of optimizing welding techniques and processes to provide strong and dependable friction stir welding (FSW) joints, which would facilitate future developments in welding technology.

CONCLUSION

The study investigates the impact of tool rotational speed and welding configuration on the tensile strength and flexural strength of high-density polyethylene (HDPE) plate friction stir welded joints. The following conclusions can be drawn: (1) At a welding speed of 5 mm/minute, a lower tool rotational speed, specifically 900 rpm, reduces angular distortion compared to the higher speeds. Double-side welding configurations also show lower angular distortion due to improved heat dissipation and material flow control. (2) Double-side welding at lower tool rotational speed also increases tensile and flexural strength, achieving joint efficiency of 71% and 85%, respectively, due to reduced heat input and material degradation. (3) Root defects are observed primarily in single-side welding passes due to inadequate thermal conductivity and incomplete welding joints at the bottom surface, emphasising the need for process optimisation and defect mitigation strategies.

Overall, optimising tool rotational speed and welding configuration is crucial for controlling angular distortion and enhancing the mechanical properties of HDPE FSW joints.

ACKNOWLEDGEMENT

We wish to convey our heartfelt appreciation to all individuals who made valuable contributions to the successful culmination of this research. We would like to express our gratitude to the staff and facilities of the Mechanical Engineering Laboratory for their invaluable support and resources, which greatly aided the implementation of our experiments and analysis.

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