Piston: Journal of Technical Engineering Vol. 9, No. 1, July (2025) 7-17

PISTON

Journal of Technical Engineering:

Characteristics of Aluminium 7075 Tool Profile for HDPE and PP Welding Against Tensile and Bending

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Received: July 05, 2025 Revision: July 08, 2025 Accepted: July 28, 2025

Abstract: The increasing demand for lightweight materials in the automotive industry has led to the replacement of metal vehicle components with polymers such as High-Density Polyethylene (HDPE) and Polypropylene (PP) to support sustainable development and emission reduction. However, welding dissimilar polymers presents a challenge due to the limitations of conventional techniques. Friction Stir Welding (FSW) emerges as a promising solution by enabling solid-state joining below the melting point. This study investigates the effect of AA7075 tool profile variations—plain cylinder, threaded cylinder, and grooved cone—on the mechanical properties and macrostructure of HDPE-PP FSW joints. Experimental welding was performed at a rotational speed of 2920 rpm and a travel speed of 30 mm/min, with analysis including tensile tests (ASTM D638), bending tests (ASTM D790), temperature measurements, and macrostructural observations. Results show that the threaded cylindrical tool yielded the highest tensile strength (4 MPa) due to effective material flow, while the grooved cone tool produced the highest bending strength (6,8 MPa) through improved vertical and radial mixing. The plain cylindrical tool showed the weakest performance with significant welding defects. Overall, tool geometry significantly influences weld quality, and selection should be based on the mechanical requirements of the application. These findings emphasize the importance of tool design optimization to enhance joint strength and structural integrity in dissimilar thermoplastic FSW.

Keywords: Friction Stir Welding (FSW), HDPE, Polypropylene (PP), AA7075 Tool, Tool Profile, Dissimilar Polymer Welding.

Abstrak: *Permintaan akan material ringan dalam industri otomotif mendorong penggantian komponen kendaraan berbahan logam dengan polimer seperti High-Density Polyethylene (HDPE) dan Polypropylene (PP) guna mendukung pembangunan berkelanjutan dan pengurangan emisi. Namun, penyambungan dua jenis polimer yang berbeda masih menjadi tantangan karena keterbatasan teknik pengelasan konvensional. Friction Stir Welding (FSW) hadir sebagai solusi menjanjikan karena mampu menyambung material dalam keadaan padat di bawah titik leleh. Penelitian ini mengkaji pengaruh variasi profil tool berbahan AA7075—silinder polos, silinder berulir, dan kerucut beralur—terhadap sifat mekanik dan makrostruktur sambungan FSW antara HDPE dan PP. Proses pengelasan dilakukan dengan kecepatan putar 2920 rpm dan kecepatan gerak 30 mm/menit, dengan analisis meliputi uji tarik (ASTM D638), uji lentur (ASTM D790), pengukuran temperatur, dan observasi makrostruktur. Hasil menunjukkan bahwa tool silinder berulir menghasilkan kekuatan tarik tertinggi (4 MPa) karena aliran material yang lebih efektif, sedangkan tool kerucut beralur menghasilkan kekuatan lentur tertinggi (6,8 MPa) berkat distribusi pencampuran material secara vertikal dan radial yang lebih baik. Tool silinder polos menunjukkan performa terendah dengan banyak cacat pada hasil las. Secara keseluruhan, geometri tool sangat memengaruhi kualitas sambungan, dan pemilihannya harus disesuaikan dengan kebutuhan mekanik aplikasi. Temuan ini menekankan pentingnya optimasi desain tool untuk meningkatkan kekuatan sambungan dan integritas struktural pada pengelasan FSW material termoplastik yang tidak sejenis.*

Kata kunci: *Friction Stir Welding (FSW), HDPE, Polypropylene (PP), Tool AA7075, Profil Tool, Pengelasan Polimer Tidak Sejenis.*

INTRODUCTION

The background of this research focuses on automotive developments that are increasingly shifting to electric-powered vehicles, which require high efficiency through weight reduction. There needs to be an emphasis on the importance of using lightweight materials to support sustainable development and reduce emissions [1]. One of the proposed strategies is replacing metal vehicle body components with polymers such as High-Density Polyethylene (HDPE) and Polypropylene (PP) [2]. Polymer materials are widely used in the automotive industry, particularly for vehicle coverings and interior components such as dashboard panels, bumpers, interior linings, engine covers, and lighting elements [3]. Although polymers offer advantages in terms of weight, the main challenge in their use is an effective joining method, considering that conventional welding techniques cannot be applied to this thermoplastic material [4].

Friction Stir Welding (FSW) method has emerged as an innovative solution for joining dissimilar polymers. Nagarajan stated that FSW allows welding at temperatures below the melting point of the material, thus avoiding adverse metallurgical reactions [1]. The Friction Stir Welding (FSW) work process consists of four stages, namely the plunging phase, the dwelling phase, the welding phase, and the exit/retract phase [5]. In the initial stage, the tool rotates and penetrates the surface of the material until it reaches the desired depth. Then, in the dwelling phase, the tool remains in place while continuing to rotate to generate heat until the working temperature is reached. After that, the tool begins to move along the joint path in the welding phase. The process ends with the tool being withdrawn from the material, which is called the exit phase. Various factors such as process parameters, tool design, and the type of material used will greatly affect the final result, including the mechanical quality of the resulting joint [6].

Various studies have examined the effect of tool shape and material as well as process parameters on the quality of FSW joints in HDPE and PP. Rezaee Hajideh found that H13 threaded cylindrical tools produced the strongest joints (23.7 MPa) and the most uniform stir zone, while plain cylindrical tools produced the weakest strength [7]. Bilici used a conical SAE1050 tool in a single-point joint, with the highest shear strength on PP-PP of 4226 N [8]. Sidhom used a carbon steel conical tool and found different optimal parameters for similar and dissimilar joints, with the best strength at rotational speeds of 3500 rpm (similar) and 2300 rpm (dissimilar) [9]. Ardyansyah used an H13 cylindrical tool showing that a feed rate of 12 mm/min produced the maximum strength (193.97 N) and the fewest defects [10]. Sugiarto used a threaded cylindrical SKD61 tool and showed the highest tensile strength (19.06 MPa) at 1800 rpm, but decreased at 2100 rpm due to excessive softening [2]. In general, tool shape, tool material type, and process parameters greatly affect the mechanical quality and macrostructure of FSW HDPE–PP joints.

FSW has become a revolutionary welding technique over the past two decades due to its energy efficiency, environmental friendliness, and high-quality joints [11]. Therefore, many studies have examined the effect of various FSW parameters as an effort to maximize the potential of FSW to produce the best welding. One effort that can be made is to choose the appropriate tool. The use of AA7075 material is an alternative choice as a tool in FSW because of its high thermal conductivity and mechanical strength so that it can inhibit the cooling rate of lava [7]. In addition, the cheaper price of AA7075 can also be an option for production budget efficiency. However, studies using AA7075 tools are still rare. Therefore, this study aims to determine the impact of the AA7075 tool profile on the characteristics of FSW dissimilar HDPE-PP welding results, so that it can provide insight for the industry in improving production quality and efficiency.

METHODS

The equipment used in this study: (a) Krisbow X 6325 milling machine (FSW modification), (b) Universal Testing Machine (UTM), (c) Bending test equipment (Three-point test). The main material of this study is a sheet of High-Density Plyethylene (HDPE) - Polypropylene (PP) which has dimensions of 125 mm x 57.5 mm and a thickness of 4 mm as shown in Figure 1. While the specifications of physical and mechanical properties can be seen in Table 1.

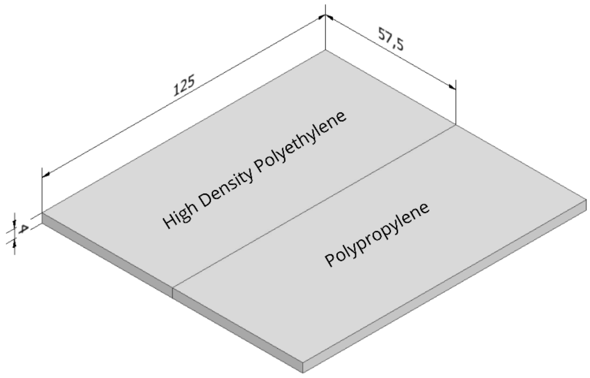


Figure 1. HDPE-PP material dimensions

Table 1. Mechanical properties HDPE-PP [12]

Mechanical Properties	Tensile Strength (Mpa)	Flexurual Strength	Hardness (SHD)
High Density Polyethylene	19	24.4	58.4
Polypropylene	30.9	47.2	71.8

The tool used uses AA7075 material with three different profile variations, namely plain cylinder, threaded cylinder, and groove cone. The dimensions of the tool profile can be seen in Figure 2.

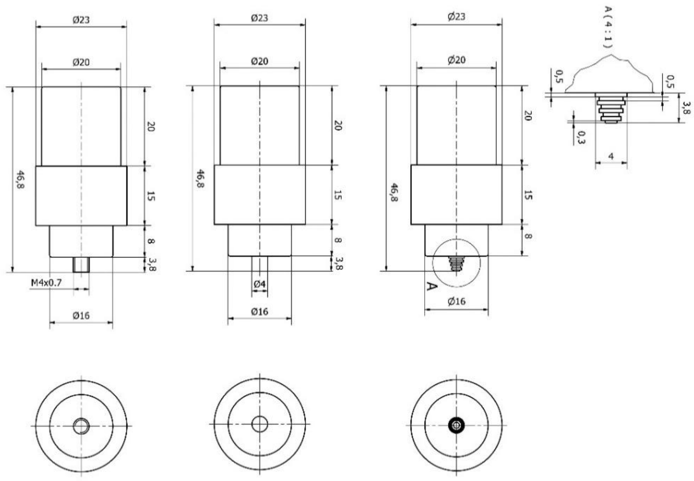


Figure 2. Tool profile dimensions

Although Friction Stir Welding (FSW) has been extensively studied and widely applied to the joining of steel and aluminum alloys, its application to polymer materials remains limited due to the absence of established industrial standards [13]. Therefore, the selection of process parameters is carried out through an experimental approach to obtain optimal joint quality [11]. In this study, the parameters were selected based on experimental results, with a rotation speed of 2920 rpm, travel speed of 30 mm/min, stirring depth of 3.90 mm, and tilt angle of 0° constantly. The FSW process scheme can be seen in Figure 3.

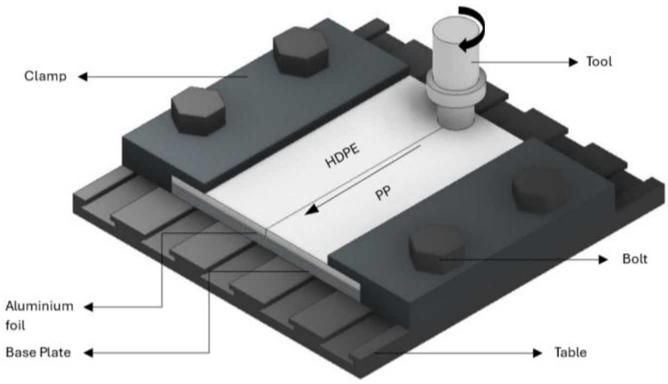


Figure 3. FSW process scheme

This research experiment was conducted at the Mechanical Engineering Laboratory of Semarang State University and Semarang Muhammadiyah University using a descriptive statistical analysis approach. This study aims to identify the characteristics of the variables studied and describe data related to variations in the shape of the pin profile made of AA7075 and its impact on the quality of the Friction Stir Welding (FSW) connection between HDPE and PP. The results of this study will be presented in the form of macro-structure photos and graphs that include tensile and bending tests. Analysis of the FSW connection results was carried out using macro-structure photos, ASTM D790 Three Point Test bending tests, and ASTM D638 type IV tensile tests. The dimensions of the test specimens can be seen in Figure 4.

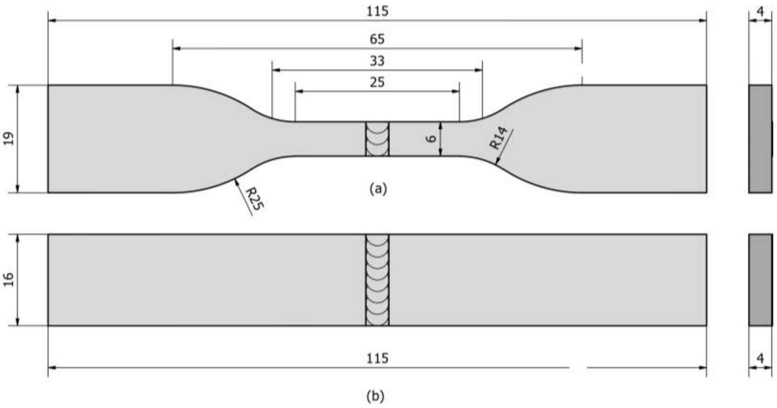


Figure 4. (a) Dimensions of tensile test specimens, (b) Dimensions of bending test specimens

RESULT AND DISCUSSION

The results of Friction Stir Welding (FSW) on HDPE and PP materials using a plain cylindrical tool shown in Figure 5 show that the main stirring zone (SZ) along the weld path appears darker and rougher than the surrounding area. This indicates the occurrence of plastic deformation and partial mixing of the material due to friction and pressure from the tool. However, the surface of the stirring zone appears uneven and is accompanied by indications of defects such as porosity, fine cracks, or irregular lines, indicating that the mixing between HDPE and PP does not occur homogeneously. These imperfections are most likely caused by the design limitations of the plain cylindrical tool which does not have stirring elements such as threads or pins. This also causes the welding results to turn black. The lack of agitation due to the plain cylindrical tool design, which does not have geometric features such as threads or grooves, results in ineffective material mixing [7], [9]. The material flow in the stir zone becomes stagnant, and the material is merely pushed rather than stirred, leading to continuous friction in a specific area. This accumulated friction generates excessive local heat, causing the temperature in the stir zone to exceed the thermal degradation threshold of HDPE and PP [9]. As a result, the polymer structure begins to break down and form carbon residue, which appears as blackening or burning in the weld joint [2]. Although AA7075 tools have good thermal conductivity, the inability to evenly distribute heat due to low agitation still leads to the formation of hot spots that trigger material degradation.

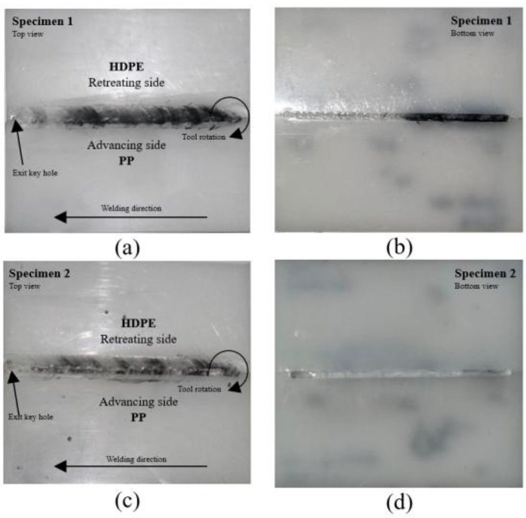


Figure 5. (a) FSW results of plain cylindrical tool specimen 1 top view, (b) FSW results of plain cylindrical tool specimen 1 bottom view, (c) FSW results of plain cylindrical tool specimen 2 top view, (d) FSW results of plain cylindrical tool specimen 2 bottom view

Based on the direction of rotation and translation of the FSW process and the orientation of the Figure 5, it can be identified that the upper part of the weld path is the retreating side (RS), while the lower part is the advancing side (AS). In RS, the direction of tool rotation is in the same direction as the translation, resulting in higher pressure and friction which causes the material flow to become more aggressive. This is evident on the upper surface of the weld path which looks rough and has the potential to cause defects such as flash or surface damage. In contrast, the AS at the bottom shows a more controlled material flow, with a relatively more stable surface although there are still indications of local porosity or roughness.

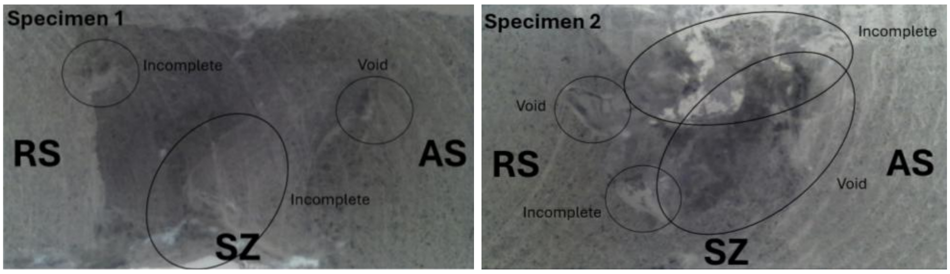


Figure 6. (a) Photo of macro structure of FSW result of plain cylindrical tool specimen 1, (b) Photo of macro structure of FSW result of plain cylindrical tool specimen 2

Based on the macrostructure image of the Friction Stir Welding (FSW) results between HDPE and PP using a plain cylindrical tool made of AA7075, a number of striking welding defects are visible, such as voids, incomplete fusion, and inhomogeneous stir zones (SZ). Voids, which appear as cavities in the joint, occur due to imperfect material mixing or trapped gas during the process, and this is exacerbated by the lack of agitation of the plain cylindrical tool that does not have cutting or stirring features such as pins or threads. Incomplete fusion or mixing that is not fully integrated is clearly visible on the advancing side (AS) and retreating side (RS), especially at the boundary between the SZ and the base material, indicating that the temperature and plastic deformation produced are not sufficient to melt the two types of polymers with different thermal characteristics. Plain tools tend to only push the material without stirring it effectively, so that the formed SZ is not uniform and contains internal defects. The combination of less than optimal process parameters does not support the flow of material as a whole, causes the formation of defective and mechanically weak joints. Therefore, to improve the quality of the joint, it is necessary to modify the tool with a more complex geometry and optimize the process parameters to produce a more homogeneous flow and mixing of the material with minimal defects.

The following are the results of FSW dissimilar HDPE-PP, variations in the profile of the threaded cylinder tool can be seen in Figure 7.

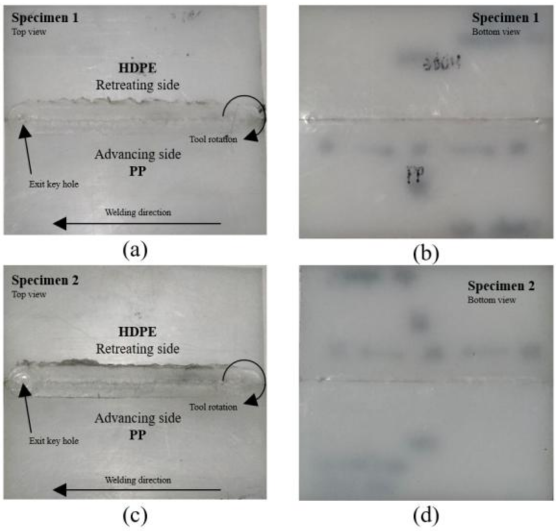
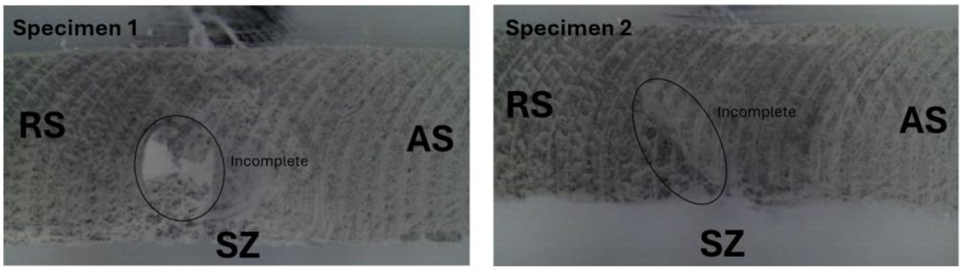


Figure 7. (a) FSW results of threaded cylinder tool specimen 1 top view, (b) FSW results of threaded cylinder tool specimen 1 bottom view, (c) FSW results of threaded cylinder tool specimen 2 top view, (d) FSW results of threaded cylinder tool specimen 2 bottom view

Based on observations of the FSW results of HDPE-PP using a threaded cylinder tool, it can be seen that the surface of the weld path is neater and more uniform compared to using a plain tool, which indicates that the mixing process and material flow are more optimal. The presence of threads on the tool plays an important role in pulling and directing the material to the stirring zone (SZ), thereby increasing the homogeneity of mixing and heat distribution. Based on the direction of the arrow and the position of the degrees listed, the top of the weld path is the retreating side (RS) and the bottom is the advancing side (AS) [7]. The retreating side (RS) and advancing side (AS) show balanced visual results., indicating that the thread tool has succeeded in reducing the flow imbalance between AS and RS. The main cause of this quality improvement is the ability of the thread to create more intensive and even mechanical agitation, thereby reducing the potential for defects such as cavities and imperfect melting. As a result, the formed stirring zone becomes more consistent, well mixed, and has the potential to produce higher mechanical strength.

The macro structure image of Friction Stir Welding (FSW) between HDPE and PP materials using a cylindrical threaded AA7075 tool shows a welding defect in the form of incomplete fusion located on the retreating side (RS) in the stir zone (SZ). This defect appears as an unfused area marked on both cross sections, indicating a failure of perfect fusion between the materials in that section. This phenomenon occurs due to differences in melt viscosity characteristics between the two materials and the irregular temperature distribution during the process. The mismatch in thermal properties between HDPE and PP leads to an imbalance in melt flow behavior, thereby hindering the homogeneous mixing of materials. The uncontrolled temperature instability further contributes to the formation of defects in the form of incomplete mixing [12].

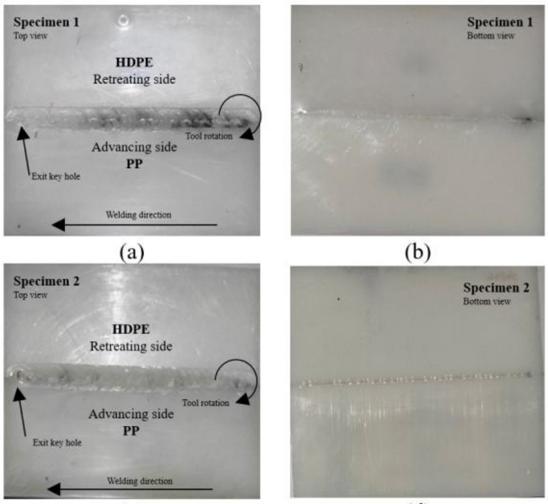


(a) (b)

Figure 8. (a) Photo of macro structure of FSW result of threaded cylinder tool specimen 1, (b) Photo of macro structure of FSW result of threaded cylinder tool specimen 2

Although the threaded tool has better agitation and heat distribution capabilities than the plain tool, these results show that the mixing process is not completely homogeneous throughout the depth or width of the weld zone, especially in the AS section. This can be caused by a combination of several factors, including less than optimal thread geometry in lifting material from bottom to top, insufficient downforce to push the material completely into the mixing zone, or local temperature imbalance due to the difference in viscosity between HDPE and PP. The result of this incomplete fusion is the formation of a joint that is not completely fused, which has the potential to be the starting point for cracks when receiving mechanical loads, as well as reducing the tensile strength and structural integrity of the joint as a whole. Therefore, although the use of threaded tools shows better results than plain tools, further optimization of the thread design, tool pressure, and process parameters is needed so that material mixing in the SZ can occur more evenly and thoroughly on all sides of the joint.

The results of FSW dissimilar HDPE-PP with variations in the profile of the conical groove tool can be seen in Figure 9.



(c) (d)

Figure 9. (a) FSW results of conical groove tool specimen 1 top view, (b) FSW results of conical groove tool specimen 1 bottom view, (c) FSW results of conical groove tool specimen 2 top view, (d) FSW results of conical groove tool specimen 2 bottom view

From Figure 9 shows the stir zone (SZ) weld groove that is more integrated compared to using a regular or plain thread tool, with a fairly clear surface appearance and shows a relatively even material flow, although irregularities are still visible in some areas. Based on the translation and rotation direction of the process and the orientation in the image, the upper part of the weld path can be identified as the retreating side (RS), while the lower part is the advancing side (AS). The cone-shaped tool with grooves provides the advantage of producing more intensive vertical and radial material flow. The grooves on the tool function to lift and spread the material evenly throughout the stir zone, thereby increasing the homogeneity of mixing between HDPE and PP which have different thermoplastic properties. However, it turns out that on the RS side the surface tends to be rougher and darker, which can indicate the presence of material flow that is too aggressive due to friction and high local temperatures, so that it is at risk of causing defects such as small cavities or excessive heat. This can be caused by an imbalance in downforce or a mismatch in the viscoelastic response between the two materials [12]. Scientifically, these results show that the grooved cone tool is able to improve the distribution of plastic deformation and heat transfer during the FSW process, but still requires optimal parameter settings so that mixing and formation of the stirring zone can occur thoroughly and without defects on all sides of the joint.

The cone-shaped tool with grooves has special characteristics in the form of a tapered shape with axial grooves designed to increase the flow of material vertically and radially during the Friction Stir Welding (FSW) process. This design allows the material flow to be deeper and more comprehensive compared to plain or threaded tools, because the grooves on the tool surface function to lift and distribute the material evenly throughout the stir zone (SZ). However, defects such as incomplete fusion and voids are still found, although they are more localized. This is generally caused by the difference in viscosity between HDPE and PP and process parameters that are not yet fully optimized, so that some parts of the material remain incompletely mixed. As a result, the resulting joints are stronger and more even compared to plain and threaded tools, but are not completely free from defects, especially on certain sides of the SZ which require further control of temperature, pressure, and tool geometry.

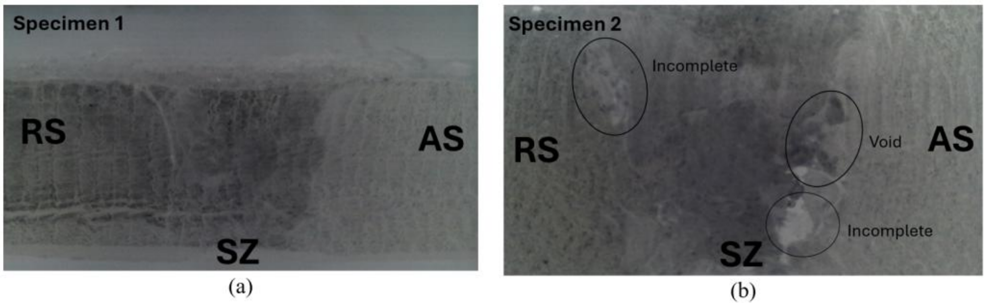


Figure 10. (a) Photo of macro structure of FSW result of conical groove tool specimen 1, (b) Photo of macro structure of FSW result of conical groove tool specimen 2

When compared with the results of Friction Stir Welding (FSW) using plain and threaded tools, the macrostructure of the FSW results with a conical grooved tool shows significant improvement, although there are still defects such as incomplete fusion and voids. Plain tools, which do not have stirring features such as threads or grooves, produce very limited material flow with a narrow and inhomogeneous stir zone (SZ), which often causes defects such as porosity, delamination, and structurally weak joints. Threaded tools provide improvements by producing a wider and more even SZ because the threads help to flow the material in a spiral manner, but still leave defects especially on the advancing side (AS) if the process parameters are not optimal. Meanwhile, the conical grooved tool has the advantage of creating more intensive and even mechanical agitation, because its axial grooves are able to lift and spread material throughout the stir zone. As a result, mixing between HDPE and PP becomes more effective and the SZ is formed with better distribution compared to the previous two tools. However, defects can still appear due to differences in material viscosity and imperfect local heat distribution. Therefore, although the grooved cone tool is the most potential choice in improving the quality of FSW joints between HDPE and PP, the tool design settings and process parameters still need to be optimized to produce homogeneous and defect-free joints.

Table 2. FSW process temperature

Profile Pin	Spesimen	Starting (°C)	Center (°C)	Final (°C)
Plain Cylinder	1	45	66	55
	2	46	58	63
Threaded Cylinder	1	46	70	70
	2	42	71	72
Groove Cone	1	40	52	63
	2	50	65	77

During the FSW process, the temperature is measured using a thermogun. There are three points where the temperature is measured during the welding process, namely the beginning, middle, and end. This temperature measurement is intended to determine the change in material temperature.

Plain cylindrical tools produce the lowest quality welding results. This is due to the absence of geometric features such as threads or grooves that can help mix the material effectively. The material flow is very limited, so that the stir zone (SZ) formed is narrow and inhomogeneous. As a result, many defects such as voids, incomplete fusion, and delamination are found, especially on the advancing side (AS), which causes the joint to be mechanically weak and structurally unfit. Threaded cylindrical tools provide significant improvements compared to plain tools. The threads play a role in pulling and directing the material flow into the SZ, resulting in more even mixing and a wider SZ. However, defects such as incomplete fusion and voids can still be found, especially if the process parameters (rotational speed, translation, and pressure) have not been optimized. The resulting joints are generally stronger than plain tools, but not completely homogeneous. Grooved cone tools show the best results among the three. The cone design facilitates penetration into the material, while the axial grooves enhance the vertical and radial flow of the material, resulting in more effective mixing distribution within the SZ. The grooves help lift and spread the material throughout the mixing zone, resulting in deeper, denser, and more even joints. Although incomplete fusion or localized voids can still be found, the number and severity are much lower than the previous two tools. The resulting joints are more homogeneous and have higher mechanical strength, making the cone-grooved tool the most potential choice in FSW welding of HDPE–PP, provided that the process parameters are properly adjusted.

Table 3. Tensile test results

Profile Tool	Sample	Width (mm)	Thickness (mm)	Area (mm^2)	Max Force (N)	Bending Strenfth (MPa)	Average Bending Strength (MPa)
Plain Cylinder	1	6	4	24	89.1	3.7	3.8
	2	6	4	24	95.4	4	
Threaded Cylinder	1	6	4	24	71.5	3	4
	2	6	4	24	122.9	5.1	
Groove Cone	1	6	4	24	79.1	3.3	3.2
	2	6	4	24	74.12	3.1	

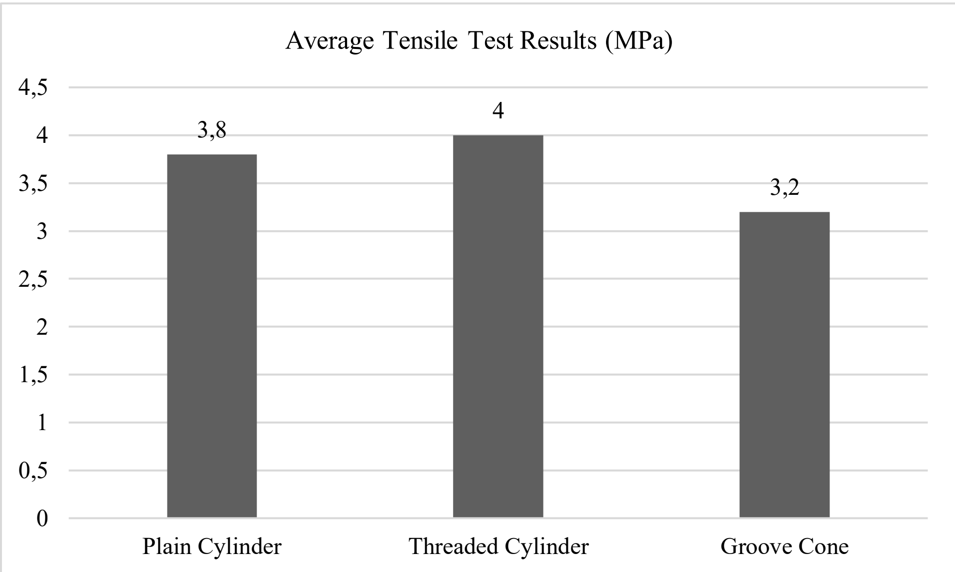


Figure 11. Average tensile strength diagram

Figure 11 shows the average bar chart of the tensile strength of the Friction Stir Welding (FSW) results between HDPE and PP using three types of tool profiles: plain cylinder, threaded cylinder, and groove cone. Based on the data in the graph, the highest average tensile strength value was obtained using a threaded cylinder tool of 4 MPa, followed by a plain cylinder with a strength of 3.8 MPa, and the lowest was a groove cone tool with a value of 3.2 Mpa.

These results indicate that although theoretically the groove cone tool has the most complex design to improve material mixing, in practice it has not been able to produce joints with the highest tensile strength. This is most likely due to the presence of defects such as incomplete fusion and voids in the weld results with the groove cone tool, as seen in the previous macrostructure. The groove cone tool is designed to generate strong radial and vertical material flow, but the longitudinal distribution (along the length of the joint) may be uneven. This results in defects such as small incomplete fusions that occur along the weld path, which are not visually apparent on the surface but significantly affect the tensile strength, as it is highly sensitive to the presence of small defects [13], [14]. This is different from the welding results using the plain cylindrical tool, where relatively large defects were found but did not occur frequently along the weld path. The groove design on the tool may not be fully optimized or process parameters such as pressure drop, temperature, and stirring time have not been adjusted to the different viscosity properties of HDPE and PP.

Meanwhile, the threaded cylindrical tool showed the best performance because the thread is able to effectively pull and spread the material along the stir zone (SZ), resulting in more homogeneous mixing and significant reduction in defects. The plain cylindrical tool, although simple, produced tensile strengths close to those of the threaded tool, indicating that under certain conditions, the simplicity of the design can still provide competitive mechanical results as long as the process parameters are appropriate. Thus, of the three tool profiles tested, the threaded cylindrical tool produced the highest tensile strength, while the conical groove tool gave the lowest tensile strength, indicating the need for further optimization of complex tools to be able to produce results in accordance with their theoretical design.

Table 4. Bending test results

Profile Tool	Sample	Width (mm)	Thickness (mm)	Area (mm^2)	Max Force (N)	Bending Strenfth (MPa)	Average Bending Strength (MPa)
Plain Cylinder	1	16	4	64	9.8	3.7	5.9
	2	16	4	64	21.6	8,1	
Threaded Cylinder	1	16	4	64	21.9	8,2	6.1
	2	16	4	64	10.7	4	
Groove Cone	1	16	4	64	17.1	6.4	6.8
	2	16	4	64	19.3	7.2	

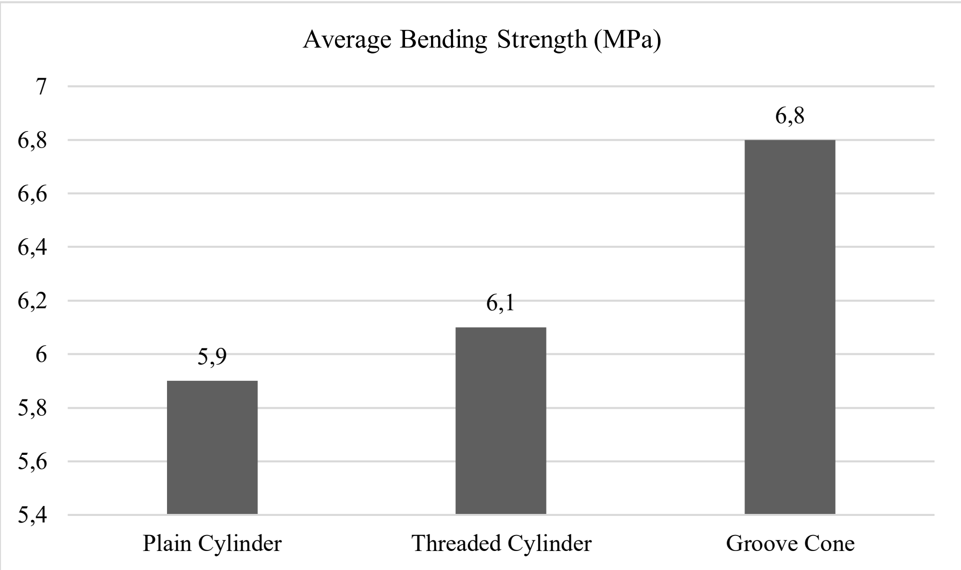


Figure 12. Average tensile strength diagram

Figure 12 shows a bar chart of the average bending strength of the Friction Stir Welding (FSW) welding results on HDPE and PP materials using three types of tool profiles, namely plain cylinder, threaded cylinder, and grooved cone. Based on the data in the graph, the highest bending strength value was achieved by the grooved cone tool with an average of 6.8 MPa, followed by the threaded cylinder at 6,1 MPa, and the lowest was the plain cylinder with a strength of 5,9 MPa.

These results indicate that in terms of resistance to bending, the grooved cone tool shows the best performance. This indicates that the axial groove design on the cone tool is able to increase the distribution of material during the welding process, resulting in a denser, more unified, and elastic joint against bending forces. Although in the previous tensile strength test this tool was not superior, in the bending test the grooved cone tool showed superiority, which was most likely due to better material distribution around the stir zone (SZ) so that it was able to withstand bending deformation. The difference in results between the tensile and bending tests of FSW HDPE-PP using the groove cone tool is caused by the characteristics of the material flow generated. The groove cone tool is designed to promote strong material flow in the radial and vertical directions, but the longitudinal distribution (along the length of the joint) tends to be uneven. As a result, small incomplete fusion defects are formed along the weld path. Although these defects are not visually apparent on the surface, they have a significant impact on tensile strength due to its high sensitivity to imperfections [13], [14]. On the other hand, the bending test results show higher values because the axial groove design on the tool produces strong, uniform, and homogeneous surface flow, resulting in better structural integrity of the outer joint area, which plays a crucial role in resisting bending loads.

The threaded cylinder tool still provides quite good results because the thread can increase material flow and help reduce defects such as incomplete fusion. Meanwhile, the plain cylindrical tool showed the lowest performance, which is in line with the characteristics of its limited material flow due to the absence of a stirring element, resulting in a less integrated joint and easy to crack when subjected to bending loads. Thus, of the three tools tested, the groove cone tool produced the highest bending strength, while the plain cylindrical tool produced the lowest, indicating that the geometric design of the tool greatly influences the mechanical performance of the joint in the context of bending resistance.

CONCLUSIONS

AA7075 tools with various profiles (plain cylinder, threaded cylinder, and grooved cone) showed limited ability to produce truly homogeneous and defect-free joints. The plain cylinder tool had the lowest agitation, resulting in a narrow stir zone (SZ) and many defects such as voids and incomplete fusion. The threaded cylinder tool increased the material flow spirally, resulting in a more even SZ and the best tensile strength among the three, but still left local defects. Meanwhile, the grooved cone tool was theoretically the most effective in distributing material because its grooves lifted and spread the material vertically and radially, but in practice it produced the lowest tensile strength, despite the highest bending strength, indicating an imbalance between mixing and joint compactness.

Each profile showed different performance in terms of macrostructure, tensile strength, and bending strength. The plain cylinder tool produced the lowest quality joints, characterized by an inhomogeneous stir zone (SZ) and many defects such as voids and incomplete fusion due to minimal material flow and mixing. The threaded cylindrical tool showed the best performance in the tensile test with an average strength of 4 MPa, because the thread is able to pull and guide the material more effectively, resulting in more even mixing and reducing defects. On the other hand, the conical groove tool, although not producing the highest tensile strength (3.2 MPa), managed to record the highest bending strength of 6.8 MPa, due to its ability to distribute the material vertically and radially intensively through the axial groove. The difference in results shows that each tool has its own advantages depending on the type of load tested. Thus, the threaded cylindrical tool is recommended to increase the tensile strength, while the conical groove tool is more effective for applications requiring high flexural resistance. These results also emphasize the importance of tool design selection and process parameter optimization in improving the quality of FSW joints between dissimilar thermoplastic materials.

ACKNOWLEDGEMENT

We would like to thank the Department of Mechanical Engineering, Semarang State University and Muhammadiyah University of Semarang and all parties involved in this research, especially fellow researchers, lecturers, and technicians at both academic institutions.

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