Characterization of Polypropylene Sheet Friction Stir Spot Welded Joint

Aris Widyo Nugroho*, Dadang Dika O. H., Cahyo Budiyantoro, Rela Adi Himarosa
Department of Mechanical Engineering, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Jl. Brawijaya, Kasihan, Bantul, Yogyakarta 55183, Indonesia.
E-mail: ariswidyo.nugroho@umy.ac.id

Abstract. A study to determine the effect of rotational speed and geometric shape of a tool on the mechanical properties of polypropylene joint using the FSSW technique has been carried out. A polypropylene sheet was cut into pieces with a dimension of 150 x 30 x 5 mm. A medium carbon steel bar was machined to fabricate welding tools. Two types of devices with shoulder angles of 0o and 5o were prepared, while the other parametric geometries were the same. While the friction stir spot welding (FSSW) process has been carried out at variations of rotational speeds of 985, 1660, and 2350 rpm, the other welding process parameters, such as tool plunge rate, dwell time, and delay time, were considered constant. The tensile shear load capacity, macrostructure, hardness, and failure mode of the joint results were then evaluated. The results revealed that using a pin tool with a shoulder angle of 5o achieved a maximum tensile shear load capacity at a rotational speed of 2350 rpm with a result of 2253 N due to its wider nugget area. The load capacity increased with the increase of rotational speed. A pin tool angle of 15o with a shoulder angle of 5o may be suggested for the tool’s chosen geometry.

1. Introduction
The friction stir spot welding (FSSW) has been developed in the automotive industry instead of resistance spot welding for joining metallic sheets [1]. The FSSW technique has been used to joint metal materials such as aluminum [7, 17, 21] and steel [1] [12]. The use of FSSW for polymeric material joint then develops, among others, polyethylene [5], polypropylene [2, 3], nylon [22], HDPE [4], and dissimilar ABS and PMMA [9]. FSSW process on thermoplastic materials consists of four stages: plunging, stirring, solidifying, and retracting [5]. A rotating tool is moved and penetrates the material up to a certain depth during the plunging process. At the stirring stage, the device rotates but does not shift. Friction between tool on the pin and shoulder with material around it generates heat and softens it. The fused materials of the upper and lower plates are mixed in the stirring process. The rotating tool is switched off and left for a moment allowing for a solidifying process under pressure from the tool shoulder to form a nugget that joins the two materials. The tool is lifted from the material on the final retracting stage, and the joining process is complete. Based on this process, FSSW on the polymer is classified as a fusion welding method [3].

During the FSSW process, heat is generated by friction rotating tool interface and work unit. Welding process parameters and tool geometry significantly affect heat forming, joint forming, and weld strength [5]. The device consists of two parts, the shoulder and the pin. The
pin generates friction heat, deforms the surrounding material, and stirs the heated material. Some researches have shown that the geometry of a pin such as a pin’s diameter [13], pin’s angle [11], pin’s thread orientation [8], pin’s length [14], and pin’ profiles [6,18], has an essential role in nugget formation. The tool’s shoulder generates heat during the welding process, forges heated material, resists the material’s ejection, and helps the movement of material around the device [23]. Shoulder geometry; the surface basin’s diameter and angle also affect FSSW results [6,15]. FSSW joint area has a keyhole in the middle of the joint, with the nuggets around it. The thickness of the weld nuggets indicates a weld bond area. Weld bond area increases with the thickness of the nuggets. The size of weld nugget thickness representing the weld bond area determines the FSSW joint’s quality [2, 4, 5]. Apart from that, the thickness of the upper sheet below the shoulder indentation also determines the FSSW joint’s strength [3].

Polypropylene (PP) is one of the thermoplastic polymers used for a variety of applications. Polypropylene is often used in the automotive, construction, aviation, and mining industries. It is widely chosen because it has high strength, anti-corrosion, and good performance at a relatively low price. Nevertheless, it also has drawbacks such as low hardness, prone to abrasion, and poor impact strength [20]. Bilici et al. [3–6] stated that the tapered cylindrical shape of pins with a concave angle of 4.5°-7.5° and a diameter shoulder ranging from 20-35 mm yield high shear tensile shear load capacity of PP with a thickness of 4 mm FSSW welded joint.

Moreover, the welding process parameter’s rotary speed at 900-1200 rpm produces a high quality joint. However, there are two visible defects from the aesthetic point: a large keyhole and a shoulder mark. It is caused by using a pin with a pin tip diameter minimum of 7.5 mm and a shoulder diameter minimum of 20 mm. To minimize those defects, it is necessary to select a smaller size of the pin and shoulder diameter without reducing the tensile shear load capacity. This research was conducted to investigate the effect of the geometry tool in shoulder concavity and the rotational tool speed process parameter with a smaller tool pin tool and shoulder diameter PP material with a thickness of 5 mm.

2. Research Method
In this study, a PP sheet with a thickness of 5 mm was cut into pieces with a dimension of 150 x 30 x 5 mm (Figure 1) using a water jet machine. According to the EN 12814-2 standard, each specimen consists of the two pieces arranged in a lap joint with an overlap area of 30 x 30 mm. An ST30 steel bar with a diameter of 20 mm was machined following Figure 2. Both types of tools with the same dimensions on the pin profile, tapered cylindrical, with a pin base diameter of 7 mm, pin length of 9 mm, pin angle of 15°, and shoulder diameter of 18 mm, were prepared. The difference between the two lay in the curvature of the surface shoulder. The first type of tool had a flat surface, while the second one possessed 5° concave surface.

![Figure 1: Tensile shear load-bearing specimen](image-url)
The welding was performed on three rotational speeds tool (985, 1660, and 2350 rpm) with the same plunging speed, stirring time, and dwell time. The results of polypropylene plate joints were characterized through several tests. Microstructures of the joint were observed using an Olympus optical microscope. Image processing using open source software, ImageJ, was also carried out to examine the joint area, such as the length of nuggets, heat affected zone, weld bonded area, and defects in the welding area.

Hardness testing was conducted using the Durometer Shore D at several points for each specimen, including raw material, upper and lower plates in the welding zone. Tensile shear load-bearing capacity was examined using standard testing for polypropylene material, namely EN 12814-2 using the Zwick/Roel Z020 universal tensile testing machine loading speed 20 mm/minute.

3. Results and Discussion

3.1. Visual Observation
In general, welding joints with two types of tools were not that different (Figure 3). However, the welding joint using tool 1 showed a more flatty surface around the keyhole than tool 2. It was because tool 2, with a shoulder angle of 5°, provided an opportunity for the material to be pressed by pins flowing through the surface shoulder concavity. This study used a pin with a profile conical shape with an angle of 15° (tapered pin). According to Bilici [2], the pin’s angle on the FSSW technique with thermoplastic materials can cause a welding force effect. The pin profile generated frictional heat and large weld thickness. In the stirring stage, the material’s temperature around the pins increases and reduces friction coefficients of the material [10]. However, if the taper angle is bigger, it generates high heat and pressure to break the plastic’s chain structure. Too large pin angle causes excessive friction heat to lower the thermoplastic FSSW welded joint [4,5].

3.2. Macrostructural Examination
Macrostructural examination of the PP FSSW welded joint is displayed in Figure 4. In the cross-section, the FSSW shows a keyhole shape mimicking the profile tool and welding zone. Two parts can be identified [16]. The first part is the weld stir zone indicating the weld bonded area or inside a two-dimensional perspective called the nugget thickness (x). The second part is the thickness of the stir zone contained in the upper material (upper sheet) under shoulder (y), as shown in Figures 4 (a) and (b). Pressure and heat arise due to the shoulder surface profile, significantly affecting the stir zone’s thickness. According to Feng et al. [10], the tensile shear load-bearing capacity of the FSSW joint is proportionally affected by the weld bond area (x) and thickness of the stir zone (y).

The surface of the welding zone below the shoulder from welding results using tool 1 is flatter. Still, with more material crushed by the shoulder and thrown out, it results in a lower surface (Figure 4 a, c and e - see orange triangle sign) than that of using tool 2. As tool rotation increases, eroded and thrown material increases, characterized by a more drop in the surface under the shoulder. On the other hand, tool 2 results in a curved surface at the edge of the
Figure 3: Top view of the keyhole and shoulder mark resulted from: tool 1 at (a) 985 rpm, (b) 1160 rpm and (c) 2350 rpm, tool 2 at (d) 985 rpm, (e) 1160 rpm, and (f) 2350 rpm, (g) side view of the joint

Figure 4: The cross-sectional area of stirred zones resulted from: tool 1 at (a) 985 rpm, (b) 1160 rpm and (c) 2350 rpm, tool 2 at (d) 985 rpm, (e) 1160 rpm and (f) 2350 rpm

shoulder (Figure 4 b, d, f-sign of the triangle). The material surface was cut according to the shoulder shape and then softened due to the friction heat on stirring processing time. The soft material was restrained, not thrown out on the keyhole neck, forming a bulge and solidifying below the shoulder at the delay time [6]. At 985 rpm rotational speed, both tools indicate a specific welding zone area with the same shape as the pin tool. It happened because the heat generated was still not high in friction. At a higher rotational speed tool, the welding zone at the bottom widens in line with the tool rotation. The nugget thickness (x) and stir area thickness (y) shown in Figure 4 was measured using ImageJ software. The results of the measurements are depicted in Figure 5.

Nugget thickness measurement results (x) support this phenomenon that the nuggets’ thickness increases with increased tool rotation on both tool types. The thickness of the nugget of tools 1 rises slightly from the rotational speed of 985 to 1160 rpm, then increases sharply at 2350 rpm. On the other hand, tool 2 shows the fluctuating x values. However, if comparing the two types of tools, the x values for tool 2 are thicker than tool 1 for each of the three tool
Figure 5: The relation between rotation speed at tool’s type and the nugget thickness

rotation levels. More concentrated pressure and heat occurred in welding with tool type 2, and no material was thrown out, resulting in thicker nuggets [2].

Measurement results for the stir zone thickness (y) indicate the different ways. While tool 1 results in a relatively constant y value, tool 2 yields gradually increasing y-values. In general, the y values of tool 2 higher than that of tool 1 except at the lowest rotational tool. The difference between the two is that the thickness (y) for tool 1 is likely to be uniform in the area below the shoulder due to pressure and friction, causing some materials to be ejected. On welding with tool 2, stir zone thickness reduction (y) only occurs at the edge of the shoulder. The thicker the middle shoulder (y), the more it reaches the lips of the keyhole. The shoulder angle plays a role in this process [5].

3.3. Hardness Test Results

For the most part, hardness testing on FSSW research on thermoplastic materials has not been carried out. In this research, hardness testing was conducted to determine the change in the resulting hardness FSSW process on PP. Hardness testing was performed on the specimen with each parameter. The test point was taken from 4 points, namely: lower sheet (point 1), welding zone lower sheet (point 2), welding zone upper sheet (point 3), and upper sheet (point 4). Position scheme testing using the Durometer Shore D can be seen in the inset in Figure 6.

The hardness testing results are presented in Figure 6. In general, the difference in hardness between points is small, ranging from 71 to 74. In more detail, several hardness values require attention. The change in the PP hardness value was caused by the phase change from solid to soft and solidified again due to pressure and friction of the shoulder and pin. At point 1 and 4 tends to be uniform with average hardness values of 71,67±0,52 and 71,83±0,25, respectively, which are the hardness values of the upper and lower sheet of raw material PP. At points 2 and 3, their hardness values (73,25±0,42 and 73,08±0,49) were found slightly higher than those mentioned earlier. These areas present the nugget thickness (x) and welding zone (y), respectively. The hardness values increase slightly, presumably the result of increased density due to heating friction. The points are also areas receiving pressure and friction because its position is directly connected with the shoulder and pin tool. Hardness values of all specimens show no significant difference with increasing tool rotational speed except for points 2 and 3, with a rotational speed of 1660 rpm showing higher hardness values.
3.4. Tensile Test Results
The lap joint tensile-shear test of PP material was carried out according to the EN 12814-2 standard with three specimens for each parameter. As a comparison, the researcher also tested the glue joint with glue G and PP material without joints as a control specimen. The ductility and ductility behavior of the FSSW joint is represented by a load diagram and the extension, as shown in Figure 7. For the most part, previous research did not present the graph. PP material without joints showed typical polymer behavior, namely, a long elastic and plastic area. The amount of plastic deformation before fracture was observed to be classified as a ductile fracture. At the same time, other joints exhibited brittle fracture behavior in the form of small plastic deformations. It indicated that the joints possessed low plasticity. The specimen broke as soon as it reached the maximum load. The tensile shear test results are presented in the tensile shear load capacity of the FSSW joint shown in Figure 8. The figure indicates that the tensile shear load capacity increases with the tool’s rotational speed without differentiating the tool type. Generally, the tensile load capacity for the joint with tool 2 is higher than tool 1 for each rotational speed variation except at 1160 rpm.

A tool with a 5° shoulder angle (tool 2) results in more shear and a higher tensile load capacity than a tool with a shoulder angle of 0°. The macro test results show that welding tool

![Figure 6: Hardness of the PP’s weld zone at several point, and the position of testing points (inset)](image)

![Figure 7: Tensile shear load versus strain of the PP’s welded joints](image)
yields more weld zone (y) and thicker nugget (x). The same result is also shown by previous research [3–6,16]. Besides, the hardness test results show a slight change in hardness due to tool type 2. Moreover, an increase in tool rotational speed supports an increase in the joint’s tensile shear load capacity. The joint efficiency ranges from 64.31- 99.03%, with the highest tensile shear load capacity of 2253 N, with a maximum tensile load of the raw material of 2275 N. The load shear load capacity of this joint is slightly higher than that of the previous research using lower length pin [19] but lower than in the other previous research, reaching 3800 N. However, the research did not mention the joint efficiency value. Besides, the research used joints with broader dimensions of specimens [3].

Figure 8: Tensile shear bearing load capacity of the PP’s welded joints

The recommended rational speed to reach the maximum load capacity was around 900 rpm [3–6, 16]. However, in this study, the speed has not reached the maximum load capacity due to its insufficient heat. Smaller dimensions of tools consisting of pin diameters and shoulder diameter might be suspected to be the causes.

4. Failure Mode

Bilici et al. [9] reported three types of FSSW joint failure on thermoplastic, namely (a) nugget pull-out failure, (b) cross-nugget failure, and (c) mixed nugget failure. All the failures are affected by the heat raised during the welding process. These conditions include conditions of not hot enough, hot enough, and excessively hot. Sometimes the nugget pull-out failure can occur due to lack of heat, but the weld zone has been formed, so part of the lower sheet is torn and carried away the upper sheet. This failure can be classified as the lowest quality of the welding joint. Types of failure for this research is presented in Figure 9 a-c. The failure pictures were classified into two types, the nugget pull-out failure, and the cross-nugget failure. At the lowest rotating

Figure 9: Typical failure for lap welded specimen (a) at the lowest rotational speed, (b) tool 1, and (c) tool 2 at a higher rotational speed
speed of 985 rpm with tool 1 and tool 2, there is still inadequate heat appearance, causing low strength short thickness of nuggets being formed to be unable to withstand the larger loads, and failure occurs (Figure 9 a). At a higher spin, the cross-nugget failure occurs in which the size of the nuggets (x) and stir zone thickness (y) are thick enough to withstand the load. In this case, the tensile shear load cuts a weld zone shorter in size. Failure in tool 1 welding is indicated by a crack starting at the end of the nugget toward the keyhole’s edge (Figure 9.b). The area has the lowest density due to being eroded and thrown by the force centrifuge from the tool rotation. However, tool 2 joint failure is indicated by cracks starting from the nugget tip to the effect profile tool’s indentation because it is in the shortest sized area (Figure 9.c). All the failures can be classified into a brittle fracture. In terms of the failure type, this fractographic observation supports the results of tensile testing.

5. Conclusion
The PP sheet with a lap joint using FSSW using a pin length of 9 mm, a pin base size of 7 mm, and a shoulder diameter of 18 mm has been successfully performed. Visually, the resulting defect was smaller. The 5° shoulder angle tool produced a larger nugget size and the welding zone width for higher tensile shear load capacity than 0°. Besides, with the tool rotation’s increasing speed (985-2350 rpm), the heat generated was higher. The stirring process was getting perfect, and the welding zone was more expansive, thus increasing the joint tensile shear load-bearing capacity. The joint tensile shear load capacity with FSSW achieves a joint welding efficiency of 99.03% for tool type 2 and a speed of 2350 rpm. The FSSW joint failures were the brittle nugget pull-out failure for low rotating speed and the cross-nugget loss for higher rotating rate. A smaller welding defect with a comparable tensile load capacity of FSSW on PP was obtained using a smaller shoulder diameter at a higher rotational speed tool.

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