Research Article

Effect of Tool Rotational Speed and Traverse Speed on Friction Stir Welding of 3D-Printed Polylactic Acid Material

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Abstract
Joining of polymers are usually carried out using adhesives that has a deteriorating quality at elevated working conditions thus limiting its application areas. Friction stir welding (FSW) is a growing solid-state welding technology, with applications including the welding of lightweight materials. FSW was recently introduced for joining thermoplastics materials and found successful. This study attempts in employing FSW to join polylactic acid (PLA)-based 3D printed engineering components and assess the effect of FSW process parameters (tool rotational speed and traverse speed) on the weld property. The present work uses the FSW process to butt weld 5 mm thick 3D printed PLA sheets with taper cylindrical profiled tool. For the experimentation, three different combinations of feed rates and pin rotational speeds are considered. Based on joint efficiency evaluation, it is found that tool rotational speed of 1400 rpm combined with 10 mm/min transverse speed produces the weld with high joint efficiency of 40%.

Keywords: Friction stir welding, PLA, Joining, 3D printing, Additive manufacturing, Tensile strength, Weld efficiency

1 Introduction

Friction stir welding (FSW) is a solid-state joining technique that uses a tool material does not melt at higher operating temperatures. FSW can produce both butt and lap joints for variety of materials. But when the lap joints are made, it is usually called as friction lap welding (FLW). The appearance of the FLW process is similar to the friction stir welding [1]. The Welding Institute in Cambridge, UK developed the friction stir process in 1991. This process dominated the field of aluminium welding in recent decades. Currently, many researchers use FSW process to join numerous other metals and alloys, such as steel, PLA, magnesium, titanium and others. Due to its energy efficiency, environmental friendliness, and usability, FSW is regarded as the most significant breakthrough in metal joining in decades, as well as a "green" technology. This approach has many benefits over common joining approaches (such as fusion welding). Easy automation, absence of expensive consumables, less distortion effect on the workpiece, and superior mechanical characteristics of weld joints are the benefits of FSW. Furthermore, it avoids all the liquid cooling issues hence the defects such as porosity, solution redistribution, reinforcement cracking and liquidation cracking are eliminated. In general, FSW was shown to be extremely tolerant of parameter and

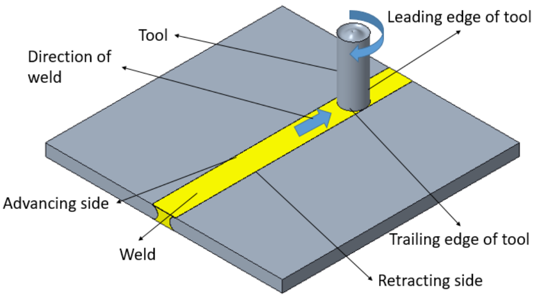

Figure 1: Schematic of friction stir welding.

substratum differences [2]. Moreover, since welding requires steel deflection at temperatures below zero, many problems associated with combining distinct alloys can be evaded and greater weld joints can be developed.

This process dwells with a non-consumable taper cylindrical profiled tool mounted on the rotating spindle. It is brought to a welding line between two sections of the sheet or strip in a butt joint way (bound together) and generates heat by rotating the tool constantly. It makes the result of rubbing between the workpiece and the tool shoulder on the one side, and a strong mechanical mixing (stirring) on the other side. This allows the substance near the tool to plasticise at extraordinarily high strain speeds, resulting in the forming of the joint [3], [4]. In more depth, the hammer stirs the plasticized material, causing the heated material to migrate through the pin tool to its backside, covering the void in the tool path as the tool goes on. While the substance cools, a solid and continuous joint forms between the two surfaces. Since FSW is not a symmetrical operation, it has two distinct sides. As shown in Figure 1, the parts of workpieces joined by a weld are mostly on the advancing or retracting side of the rotating tool. The rotating orientation of the tool is opposite to the direction of travel and parallel to the direction of the metal flow on the retreating side. On the advancing side, tool rotation is same as the direction of the tool movement and the direction of the metal flow [5]. FSW of thermoplastics have shown considerable advancements in terms of quality of joints produced. Being a solid state welding, FSW has good inheritance of the parent material properties and doesn't alters it [6]–[8]. The welds produced in polymers using FSW has good mechanical properties and retains the base material physical properties [9]–[11].

PLA resin, also known as polylactic acid, is a plant-based plastic that is commonly made from corn-starch as a raw material. It is a thermoplastic aliphatic polyester and most commonly used natural raw material in 3D printing. PLA is entirely made of recycled biodegradable raw materials [12]. PLA is one of the most widely used additive manufacturing materials for all 3D printing materials. Since it can be printed at a low temperature and does not require a heated bed, it is the default filament for most extrusion-based 3D printers. PLA is an excellent first material to use because it is simple to print, cheap, and produces components that can be used for a range of purposes. It is still one of the most eco-friendly filaments on the market right now. PLA is derived from corn, sugarcane, maize starch, sugar cane, tapioca roots, and even potato starch; hence it is organic, and most significantly biodegradable. Due to the aforementioned reasons, PLA is chosen for the present study. This material has many benefits over common materials such excellent dimensional precision, longer shelf life, stiff and solid and available at low cost. But it also has some limitations such as (a) lower heat tolerance, (b) It is may creep and require cooling fans, (c) filament can become fragile and tear over time (d) not ideal for use outside (sunlight exposure) [13]. PLA is strong, firm and biodegradable but is fragile since it is not made of crude oil. PLA possesses endurance, good appearance and durability.

In contrast with petrochemical plastics such as ABS or polyvinyl alcohol (PVA), PLA is therefore the most ecologically safe 3D printing material. Many of these prints are often drawn to the wide variety of colours, translucencies and a glitzy-shiny feeling for show screens or limited household uses. Being thicker and harder than most 3D printed materials, makes it suitable for 3D printing. It is transparent and can be painted with variable levels of opacity and illumination. These textiles are usually less likely to warp and shrink, since they are adapted for small parts. Printed products typically look and sound glossier. One notable disadvantage is that extreme heat cannot be resisted, so standard PLA softens around 50°C. This can however be seen as a benefit for rapid patching, folding or welding of printed parts.

Polymers are the primary and first choice materials when it comes to 3D printing. The most popular and economic 3D printing technology, Fused Deposition

Modeling (FDM), has thermoplastics as its raw material. Acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polylactic acid (PLA) and polyethylene terephthalate (PET) are the materials widely used in FDM process. Initially 3D printed parts were used for prototyping alone, whereas invention of new polymeric materials and increased 3D printing capability have capacity enough to produce ready-to-use components in the areas of automobile (ABS), aerospace (PC), electronics and biomedical engineering applications (PLA). Though FDM has gained popularity and economic viability, its performance is dependent on the build volume. As the build volume increases, its accuracy decreases, due to longer printing duration [14]. Even, increasing the nozzle diameter could be an option to reduce build time, but that too has compensation in accuracy. Hence, joining of 3D printed polymers is now within the researchers' interest. Adhesives were earlier choices for joining polymers. Recently, FSW and ultrasonic welding methods are employed by researchers. Introducing FSW in 3D printing industry will help with the segmentation process, normally the segmentation process done by using adhesives. FSW has more advantages compared to the adhesives, because aspects like change in temperature, contamination and surface condition can vary the properties of adhesives and cause it to fail. Friction stir welding offers better joining than the adhesives and it offers high joint strength. Hence this work aims in employing FSW process to join 3D printed PLA material and study the effect of FSW process parameters on its weld strength.

2 Method

2.1 *Fabrication of fixture*

A welding fixture is used to perform FSW in a milling machine, on which the plates to be butt welded are fastened. For this purpose, a welding fixture and clamping setup is specially designed for a vertical milling machine. The screw clamps are built to keep the work parts rigidly during the welding process, which is a vital one [15]. Taking into account the tool's lateral and transverse rotation, the workpiece should not be able to move in order to avoid welding defects. There are three major parts of the designed fixture are a backing plate, pressure bars and fasteners.

Figure 2: Fabricated backing plate.

2.1.1 Backing plate

The term "backing" refers to the material used at the root of a weld joint to support molten weld material [16]. Its aim is to make full joint penetration easier. In this experimental study, the backing plate has served for the purpose of holding the workpiece also. Since the working specimen is only PLA, the mild steel material strip is adequate to keep it in place [17]. The backing plate is made of a single piece of mild steel that has been cut into intrinsic shapes to create a space into which the workpiece can be placed. The length of the backing plates and fixtures is chosen to suit the available milling machine work table, while the width can be increased based on the dimensions of the specimen's dimension.

By the measurements it was found that a length 130 mm required for strip. Hence, a 150 × 130 mm mild steel strip was taken and it was drilled to 12 mm diameter that can carry M12 bolt. The holes are needed to be drilled at a distance of 31.4 mm from the centreline of backing plate, so that it will align with the work bed of vertical milling machine. The backing plate was modelled with a help of Creo Parametric 5.0, then the backing plate was fabricated with a help of vertical drilling machine. The Figure 2 shows the fabricated backing plate with the exact location of key slots for the fasteners.

2.1.2 Pressure bars

The vertical clamping forces to the workpieces were applied by means of pressure bars and fasteners (bolts and nuts). These are used to apply pressures to maintain consistent clamping forces and temperature distribution across the welded frames [18]. The

Figure 3: Fabricated pressure bars.

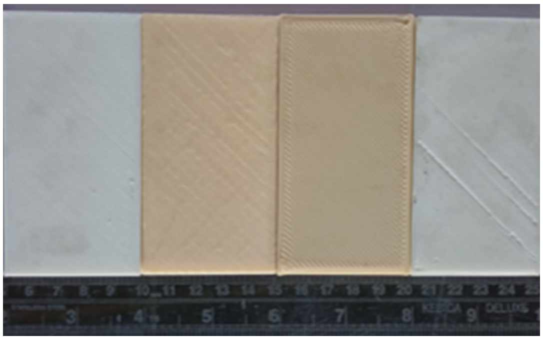

Figure 4: Samples of 3D printed PLA workpieces before welding.

design facilitates to use two pressure bars to hold the workpieces. The Pressure bars were also modelled by the help of Creo Parametric 5.0. To fabricate the pressure bars, the 30 mm mild steel strip was cut into 150 mm length, two strips were cut and then by using drilling machine with 12 mm Diameter drill bit, two holes were made on both of the pressure bars at a sufficient distance to match the backing plate and the T-slot milling machine table. The Figure 3 shows the fabricated pressure bars with the exact location of key slots for the fasteners.

2.2 *Preparation of PLA plates*

A 5 mm thick 3D printed PLA sheet was used to conduct the experiment. The dimensions of the printed PLA sheets are 100 × 50 × 5 mm. 3D Printer developed by FABX was employed to print the workpieces. The PLA used is of medical grade having printing temperature of 185°C. Then it was fed to the 3D printer nozzle, the specifications of the workpieces was also fed to 3D printer nozzle [19]. Then the PLA specimens were 3D printed according to a specification of 100 × 50 × 5 mm size, 100% infill with a nozzle temperature vary from 180 to 190°C. Raster orientation is 45°/–45° [20]. Figure 4 shows the final 3D printed workpieces.

2.3 *Tool fabrication*

To perform FSW on 3D printed PLA specimens, a tool is manufactured as required by weld joint. FSW tool helps in creating the frictional contact at the joint and facilitates the weld pool dynamics. A tool with a taper cylindrical nose radius was chosen with a view to

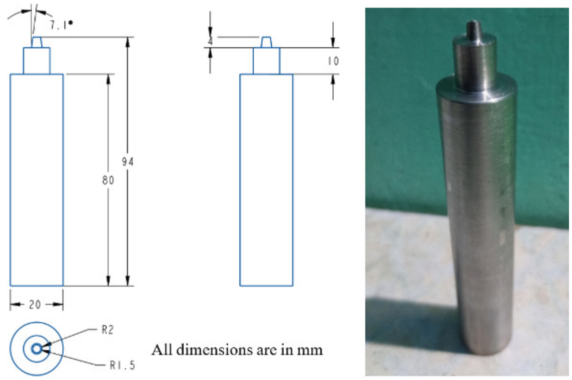

Figure 5: FSW tool.

performing FSW. Since the specimens are made of soft PLA, stainless steel was selected for the tool material [21]. The pin and shoulder were respectively 4 mm and 10 mm in diameter. The pin was 4 mm thick to prevent touch of the back plate since the workpiece had a thickness of 5 mm. The tool was initially modelled using Creo Parametric 5.0, the various views of the tool to depicting all the dimensions is shown in the Figure 5. A 20 mm stainless steel rod of length 100 mm was selected to fabricate the tool. According to the desired size, the tool is machined from the selected stainless steel rod. The developed tool is shown in Figure 5.

2.4 *FSW of 3D printed PLA material*

Friction stir welding was performed in a vertical milling unit with the fabricated tool and fixture setup. The feeding rate was determined by the machine table of the VMC, which uses a high-speed spindle in a fixed position with different rotation speeds.

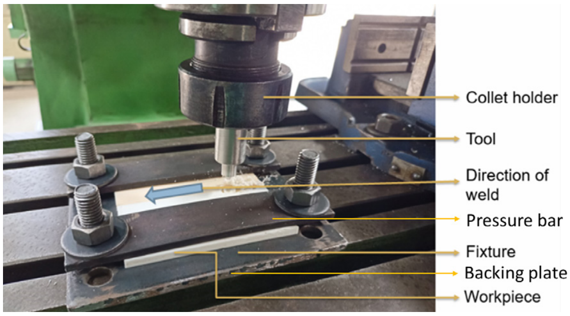

Figure 6: Setup used for the FSW of PLA plates.

In order to perform the FSW, the fixture attached to the vertical milling machine bed with a help of fasteners. Then the workpieces were clamped firmly by the fixture, arresting all the degrees of freedom hence the workpiece cannot be moved [22]. Then the tool is clamped vertically on the vertical milling machine by the help of collet. The welding setup is shown in the Figure 6. After the compilation of setup arrangement, the welding process was carried by adjusting the desired tool rotational speed and workpiece feed. Based on initial trials and the speed options available in the vertical milling machine, the window for FSW process parameters has been selected. Table 1 shows the parameter combination used for FSW. To weld all of the samples, various welding parameters such as tool rotational speeds and weld speeds were used.

Table 1: Experimental combinations

Sample No.	Tool Rotational Speed (rpm)	Traverse Speed (mm/min)
S1	700	10
S2	700	14
S3	700	20
S4	1400	10
S5	1400	14
S6	1400	20
S7	2000	10
S8	2000	14
S9	2000	20

3 Results and Discussion

3.1 *Tensile strength*

Tensile testing is a major materials science and engineering procedure, involving the application of controlled stress in a sample until it breaks. A tensile

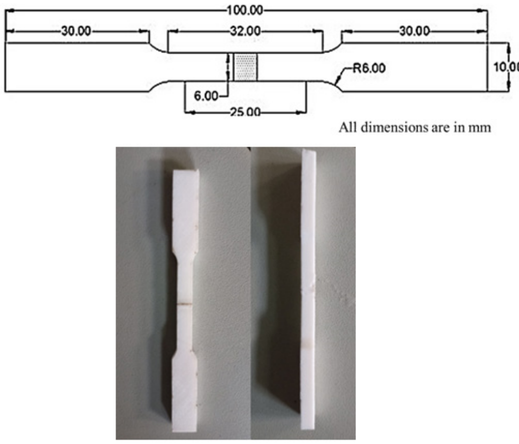

Figure 7: Tensile specimen prepared as per ASTM standard.

test is used to determine the metrics such as flexural strength, rupture force, maximum length and area reduction. These metrics can be applied to measure the modulus, the Poisson ratio, the power and tensioning properties. The most popular method for determining the mechanical properties of isotropic materials is uniaxial tensile testing. Biaxial tensile testing is used on certain materials alone [6], [13]. A tensile specimen is a standardised cross-section of a sample. There are 2 shoulders and a central gauge (section). The shoulders are broad to make it easier to grip, and the cross section of the gauge has a smaller cross section for deformation and failure in the region.

Tensile testing is normally done at a product testing facility. The universal testing machine is the most common tension testing machine used for this purpose. This device contains two crossheads, one for adjustment of specimen length and the other for stress on the test specimen. Electronic tensometer, having 25 kN capacity with maximum displacement of 600 mm, is used to perform tensile test. The speed limit was set to test speed of 0.2 mm/min. The ASTM E08 tensile testing protocol is one of the most widely used standard for tensile testing [18]. The parameters like extension, ultimate tensile strength, Poisson's ratio, and yield output strength are all measured by the ASTM E08 standard and the specimens prepared for the testing as per ASTM standard are shown in the Figure 7. In order to conduct the testing, the machine must be capable of testing the welded test specimen. Distance, strength, precision, and accuracy are the four

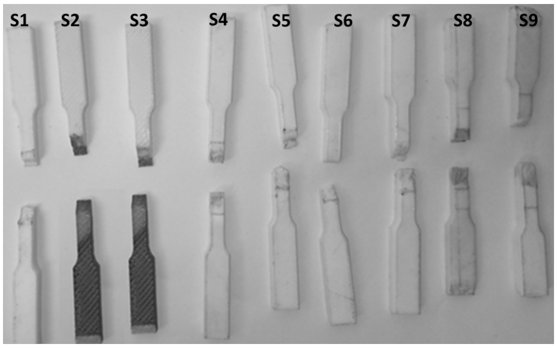

Figure 8: Tensile tested specimens.

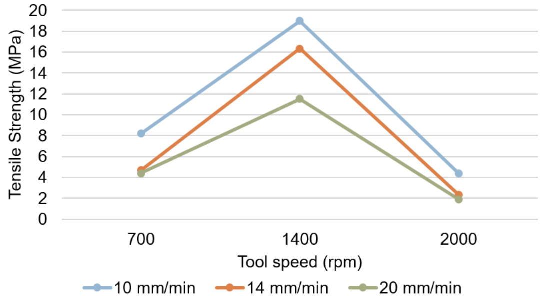

Figure 9: Effect of tool rotational speed on tensile strength.

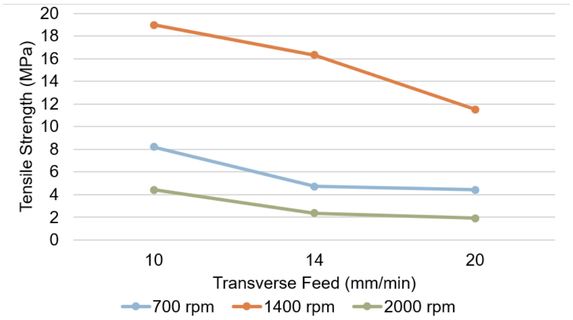

Figure 10: Effect of traverse speed on tensile strength.

key parameters to be assessed. The machine's strength potential refers to its capacity to generate enough power to divide the specimen. To correctly mimic the actual application, the computer must be able to apply force quickly or slowly. Finally, the device must be able to determine the measuring length and applied forces reliably and accurately; for example, a large machine that calculates long elongations cannot be used with a vulnerable material that is only slightly elongated before fracturing. Since the machine twists the specimen as it is misaligned, either at an angle or to one side, it is important to align the test specimen in the test machine.

This is particularly bad for fragile materials, as the findings would be drastically skewed [12]. Between the grips and the test unit, spherical seats or U-joints may be used to reduce this condition. One end of the test specimen was held in the stationary clamp or the bottom clamp and the other end is clamped by the moving clamp or the top clamp without any misalignment. Then the tensile load was applied on the specimen. When the load crosses the ultimate tensile strength of the welded specimen it tends to break. The tensile analysis was performed first on the 3D printed PLA (Base material) measure its resistance, and then the experiments were done on the welded specimens to compare the outcomes. Nine test samples were taken for the tensile testing process. The Figure 8 shows images of all the tested samples and it's clear that the breakage has happened in the weld region in all samples. To conduct all nine tensile strength testing tests and assess joint efficiency, the two welding parameters such as tool rotation and traverse velocity were used with their corresponding concentrations. By varying tool speeds, traverse velocity, the 3D printed PLA samples were welded using a taper cylindrical profiled tool and the tensile power is noted as given in Table 1.

3.2 *Variation of weld strength with various parameters*

All the samples were welded with varying welding parameters such as tool rotational speeds and weld speeds and tested successfully. The obtained results are tabulated in the Table 2. The load vs. extension graphs are shown in Figures 9 and 10. It depicts the tensile strength of 3D printed PLA samples welded using a conical profiled tool at various tool rotational speeds and traverse speeds. The parameters like ultimate tensile strength, yield strength were measured by using the tensile process and the joint efficiency was found to determine the optimum weld efficiency and its parameters. The test sample subjected to 1400 rpm of tool rotational speed and 10 mm/min of transverse speed has shown good results in tensile test. It gives a high tensile strength of all the specimens.

Table 2 shows the difference in tensile strength with respect to tool rotational speed and transverse speed. Figure 10 shows that as the tool rotational speed

Table 2: Experimental results of tensile tests

Sample No.	Tool Rotational Speed (rpm)	Traverse Speed (mm/min)	UTS (kgf)	UTS (MPa)	Joint Efficiency (%)
S1	700	10	0.835	8.1913	17.2877
S2	700	14	0.48	4.7088	9.9378
S3	700	20	0.45	4.4145	9.3167
S4	1400	10	1.935	18.9823	40.0621
S5	1400	14	1.665	16.3336	34.4720
S6	1400	20	1.175	11.5267	24.3271
S7	2000	10	0.45	4.4145	9.3167
S8	2000	14	0.24	2.3544	4.9689
S9	2000	20	0.195	1.91295	4.03726
Base material as fabricated			4.83	47.3823	-

is increased from 700 to 1400 rpm, the weld strength increases, but decreases as the tool rotational speed is increased from 1400 to 2000 rpm. At a lower tool rotational speed of 700 rpm, the heat produced during welding is insufficient to soften the steel. As a result, at a lower tool rotational speed, the weld strength is poor. At a tool rotational speed of 1400 rpm, further stirring of the tool pin raises the weld strength [23]. This makes a smoother content mixing. However, as the tool rotational speed is increased to 2000 rpm, the strength decreases. The material degrades as a result of the high tool rotational speed, resulting in weakened welds. Because of the conical shape of the conical pin, it has a strong tendency to mix the material, resulting in high polymer flowability. As a result, high speeds are incompatible with high tensile strength.

Figure 10 shows that at a lower traverse speed of 10 mm/min, the weld strength was found to be high. At the fastest traverse speed of 20 mm/min, the weld strength is poor. At higher traverse speeds, the material mixing is insufficient. This is due to the fact that the material has less time to move from the retreating to the advancing side of the weld [24]. As a result, as the traverse speed increases, the weld strength decreases [25].

4 Conclusions

Although friction stir welding is a relatively recent solid-state joining technique, it was originally developed for aluminium alloys. Extensive testing has been done to see the applicability of FSW technology for thermoplastic materials, and the results have been promising. While thermoplastics are mostly used for 3D printing process, the FSW has the potential to replace adhesives in segmentation. Since adhesive properties are affected by the change in temperature, contamination and surface condition, FSW sees a promising adaptation in this field.

In this study, the FSW was used to analyze the joining behavior of 3D printed PLA strips. The tensile failure load and joint efficiency of PLA specimens have been evaluated. The impact of tool rotational speed and traverse speed on tensile failure load has been investigated experimentally. Upon review of results, it is found that poor welds resulted from the low tool rotational speed of 700 rpm and also the high tool rotational speed of 2000 rpm. The welded specimen's tensile strength was found to be strong when the tool rotational speed was held moderate (1400 rpm). The welded specimen was weak due to the fast traverse speeds of 20 mm/min and 14 mm/min. It was discovered that a low traverse speed of 10 mm/min was successful in achieving higher weld power. The experimental graph shows that specimens have the qualities of a brittle material as it did not elongate much distance. A highest joint efficiency of 40% has been achieved in FSW of PLA at tool rotational speed of 1400 rpm and traverse speed of 10 mm/min.

The welding process was conducted using a vertical milling machine, but more efficient and accurate welding may be obtained with a help of a CNC milling machine. More convergence in the tool rotational speed and welding speed can be achieved by employing suitable optimization techniques. Studies on keyhole defects and effects of other FSW process parameters can also be taken up as future works. As PLA is a bioplastic, the results of these studies find applications in product development of new biological implants, where build volume of 3D printers becomes a constraint. Implications of this will be a result of economical product development. Same methodologies can be applied to other materials as well which struggles with build volume factor.

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Conflict of interest

Authors declare no conflict of interest including any financial, personal or other relationships with other people or organizations that can influence their work.

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