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Welding of thermoplastics printed by fused filament fabrication: A critical review of joining mechanisms and relationships between processing, structure, and properties

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Abstract: Fused filament fabrication (FFF) technology, also known as fused deposition modeling (FDM), enables the production of thermoplastic components with complex geometries, but remains limited by the printer's build volume. Welding can join separately printed components. However, layered structures, infill configurations, porosity, and interlayer bonding affect joint formation and strength. This article critically reviews six welding techniques for FFF-printed thermoplastic components: friction stir welding, friction stir spot welding, rotary friction welding, ultrasonic welding, laser joining, and microwave-assisted welding. The review focuses on joining mechanisms, process parameters, material characteristics, mechanical performance, and failure mechanisms. The results indicate that joint quality depends on the interaction among welding parameters, polymer type, infill structure, tool or interface design, and joint configuration. Increasing process energy does not always improve joint strength because excessive heating can cause thermal degradation and deformation, while insufficient material consolidation can limit joint integrity. Direct comparisons between techniques are still limited by differences in materials, specimen geometries, joint configurations, and testing methods. Evidence regarding microwave-assisted welding for joining separately printed components is also still limited. Future research needs to integrate printing and welding parameters, correlate structural characteristics and defects with mechanical performance, and improve the consistency of testing and reporting. Such an approach is necessary to clarify the relationships between process, structure, and properties and to support the development of reliable joints for engineering applications.

Keywords: fused filament fabrication; thermoplastic welding; friction stir welding; ultrasonic welding; laser joining; process-structure-property relationship

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1. Introduction

Advances in additive manufacturing technology, particularly fused filament fabrication (FFF)-also known as fused deposition modeling (FDM)-enable the production of thermoplastic components with complex geometries and high design flexibility [1], [2], [3], [4], [5]. However, the printer's build volume still limits the size of components that can be produced, whereas manufacturing requirements often necessitate assembling multiple components into larger or functional structures. Welding can help overcome these limitations by joining separately printed components. Nevertheless, the formation of joints in FFF-printed components is influenced by characteristics formed during printing. Layered structure, raster orientation, porosity, interlayer bond quality, and surface conditions can affect the material's thermal and mechanical response as well as bond formation at the joint interface. Therefore, joint performance must be analyzed by considering the

interaction between the initial characteristics of the printed components and the welding process conditions [6], [7].

Various techniques have been studied for joining 3D-printed thermoplastic components, including friction stir welding (FSW), friction stir spot welding (FSSW), rotary friction welding (RFW), ultrasonic welding, laser joining, and microwave-assisted welding. These techniques have different joint formation mechanisms and process requirements. FSW and FSSW use friction-generated heat, along with deformation and material flow around the cutter, while RFW relies on friction heat from relative motion at the component interface. Ultrasonic welding uses high-frequency mechanical vibrations to create conditions that support bond formation. In laser joining, energy distribution and joint formation depend on the materials' optical absorption characteristics and the joining configuration, whereas microwave-assisted welding depends on the interaction of microwaves with the material or the energy absorber used. These mechanistic differences affect heat distribution, material movement and consolidation, defect formation, and the joint's mechanical properties. In FSW, for example, the tool rotation speed and welding speed can affect the strength of PLA joints [8]. However, the relationship between process parameters and joint performance is not always linear and may vary with polymer type, joint configuration, and the internal structure of the printed component. Furthermore, differences in specimen geometry, welding conditions, and testing methods must be taken into account when comparing results from different studies.

Previous reviews have discussed various joining approaches to address print volume limitations, including welding techniques for FFF-printed components [9]. Nevertheless, a comparative evaluation is needed that consistently links pre-welding component characteristics, process conditions, joint formation mechanisms, defect characteristics, and reported mechanical performance. Therefore, this article aims to critically evaluate six welding techniques for FFF-printed thermoplastic components, analyze the factors influencing joint formation and performance, and identify limitations in the experimental evidence and research gaps. The main contribution of this article lies in synthesizing process-structure-property relationships to explain how printing characteristics and welding conditions relate to joint formation and performance.

This article employs a conceptual and integrative literature synthesis approach rather than a systematic review. Findings from previous studies are compared and interpreted based on welding mechanisms, process parameters, joint characteristics, and mechanical test results, while accounting for the limitations of such comparisons due to differences in material, joint configurations, and testing methods. This synthesis is expected to clarify the factors that influence joint reliability and help establish research priorities for developing FFF/FDM-printed thermoplastic components joined by welding.

2. Welding technologies for 3D-printed thermoplastic components

Welding technology is one post-processing approach for joining thermoplastic components produced via additive manufacturing into larger or functionally integrated structures. This approach helps overcome the limitations of 3D printer build volumes, allowing components to be produced separately before assembly [9]. Various techniques have been studied for joining thermoplastic components produced via material extrusion (MEX), including those manufactured using FFF. For example, a study on PLA and wood-particle-reinforced PLA composites compared adhesive bonding, direct printing, and ultrasonic welding. Among these three approaches, ultrasonic welding produced the highest average shear strength under the reported test conditions, at 16.4 ± 0.5 MPa [6]. Other studies have examined friction stir welding (FSW) on 3D-printed PLA components [10], spin friction welding or rotary friction welding on MEX-produced components [7], and laser joining on 3D-printed PLA components [11]. In addition, ultrasonic-assisted friction

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stir spot welding (UA-FSSW) has been investigated as a hybrid process for joining PLA Plus and carbon-fiber-reinforced PLA (PLA-CF) [12], while microwave-assisted welding has been evaluated for joining separately printed MEX components [13].

Each technique has different joint formation mechanisms, process requirements, and performance characteristics. Joint quality can be influenced by the type of polymer, the internal structure of the printed components, the joint configuration, and the welding parameters. Therefore, the results of different studies must be evaluated by considering the experimental conditions, mechanical performance indicators, and reported failure mechanisms. This section discusses the operating principles and experimental evidence for these six welding techniques, focusing on process parameters, interface characteristics, mechanical performance, and the limitations of each technique.

2.1 Friction stir welding

FSW is a joining method that utilizes heat generated by friction and mechanical deformation to soften and displace the material around a rotating pin. In this process, the pin penetrates the joint area and is moved along the joint line with an appropriate axial force. The rotational and translational motion of the pin generates heat and deforms the material around the stir zone. The softened material then flows and consolidates behind the pin, forming a bond between the components after the cooling process. The operating principle of FSW is shown in Figure 1. FSW is conventionally classified as a solid-state welding process because it does not require complete melting of the base material. However, in thermoplastics, local thermal conditions depend on the polymer type and process parameters; therefore, without temperature data and joint-zone characterization, significant softening or local melting cannot be ruled out.

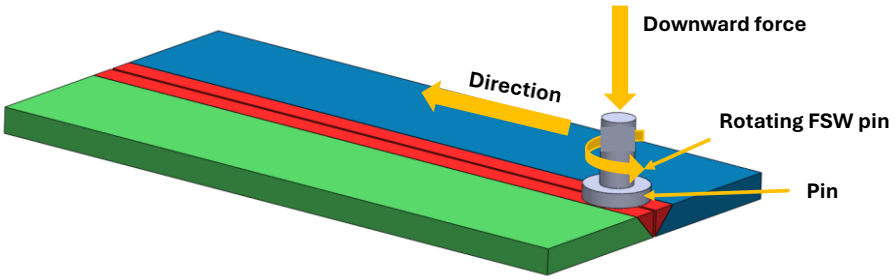


Figure 1. Working principle of FSW

The performance of FSW joints is influenced by process parameters that determine heat generation, material deformation, and consolidation in the joint region. The two main parameters that have been extensively studied are the pin rotation speed and the welding speed. In the butt welding of 5-mm-thick 3D-printed PLA plates, a combination of a rotational speed of 1,400 rpm and a welding speed of 10 mm/min resulted in a tensile strength of approximately 18.98 MPa with a joint efficiency of about 40% [8]. For ABS components produced using the material extrusion method, statistical analysis showed that rotational speed, welding speed, and pin geometry significantly influenced joint strength [14]. These findings indicate that FSW performance is determined not only by a single parameter but also by the interaction between process conditions, material characteristics, and joint configuration. Therefore, parameters that produce a relatively good joint in one type of polymer may not yield the same results in another polymer, even when the welding configuration is similar.

In addition to welding parameters, the internal structure of 3D-printed components must be considered because infill density determines the distribution of material available for the mixing

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and consolidation processes. Low density can lead to the formation of internal voids, meaning that material in the joint area is not always available in sufficient quantities to form a continuous bond. For PLA Plus components, local infill densities of 20%, 60%, and 100% were evaluated using a triangular pin [15]. The highest tensile strength, 17.83 ± 0.68 MPa, was obtained at a local infill density of 60%, a rotation speed of 1,750 rpm, and a welding speed of 20 mm/min. In contrast, for the 20% local infill configuration, the highest reported tensile strength was 3.32 MPa. These results indicate that adjusting the local infill density has the potential to improve joint performance without requiring all components to be printed at maximum density. However, the 60% density represents only the best condition within the tested parameter range, not a universal optimum value for all FSW configurations.

The effect of infill density was also observed in a study of portable FSW on PLA with infill densities of 15% and 100%. Specimens with 100% infill exhibited better structural homogeneity compared to those with 15% infill, which showed poorer consolidation, even when filler material was added [10]. These findings indicate that the addition of filler material alone may not necessarily overcome the consolidation limitations in low-infill structures. These results also confirm that the initial material density is a critical part of the boundary conditions for the welding process, not merely a printing parameter that can be disregarded once the component is manufactured. However, infill density must still be analyzed alongside pin geometry and welding conditions, as these factors affect material flow and distribution in the joint zone.

Pin geometry is another factor that influences the mechanical interaction between the pin and the material during welding. The shape of the pin can affect material movement, strain distribution, and the formation of the joint region. In a study of portable FSW on PLA with 100% infill, cylindrical pins produced a tensile strength of 8.02 ± 1.42 MPa, while truncated conical pins produced 6.25 ± 1.43 MPa. The highest reported joint efficiency for this configuration was approximately 27% relative to the base material with 100% infill [10]. Meanwhile, in PLA Plus components with 60% local infill, triangular pins yielded the highest tensile strength of 17.83 ± 0.68 MPa under the tested process conditions [15]. This difference cannot be attributed solely to pin geometry, as the two studies used different welding equipment, specimen designs, and process conditions. Thus, the effectiveness of pin geometry must be evaluated in relation to material characteristics, internal structure, and welding parameters.

The relationship between pin geometry and internal structure is also evident in the welding of PLA composites reinforced with 10% by weight chromium particles. The combination of square pins and a tri-hexagonal infill pattern yielded a joint strength of 30 MPa with an efficiency of 108% in PLA composites reinforced with 10% by weight chromium particles [16]. The study also showed that the tri-hexagonal infill pattern retained 46.1% of the hardness, compared to 34% for the linear pattern. Conical pins produced lower joint strength in the configurations studied. These results reinforce the indication that pin geometry and infill patterns can interact in determining joint performance. However, the joint efficiency of 108% must be interpreted in light of the reference material and the definition of efficiency used in the study; this value does not in itself prove that the joint is superior to the base material in all mechanical aspects. Furthermore, because the study used chromium-reinforced PLA composites, the results cannot be directly generalized to unreinforced PLA or other polymers.

The joining of dissimilar materials has also been studied in 3D-printed PLA and PLA-Wood components, with a joint efficiency of 74.3% based on tensile strength and 142.68% based on flexural load [17]. These differences indicate that joint performance depends on the type of loading and the reference parameters used. An efficiency above 100% in flexural testing does not necessarily indicate that the joint has better tensile strength or overall structural performance than the base material. The joining of components produced via different manufacturing methods has also been

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studied using FSW, specifically for 3D-printed polymethyl methacrylate (PMMA) components joined to conventionally extruded PMMA sheets. The highest joint efficiency reached 1.36 in tensile testing and 0.98 in flexural testing, at a rotation speed of 900 rpm and a welding speed of 6, mm/min [18]. These values correspond to efficiencies of 136% and 98% relative to the reference material. These results demonstrate the potential of FSW to join components with different manufacturing characteristics; however, their interpretation must account for the reference material, joint configuration, and testing methods.

Thermal conditions also play a role in determining the quality of FSW joints in 3D-printed polymers. The use of stationary-shoulder friction stir welding (SS-FSW) with auxiliary heating on PLA and polyether ether ketone (PEEK) components resulted in better joint surface quality compared to the use of a rotating shoulder under the tested conditions. For PLA, lower welding speeds are associated with improved joint efficiency, whereas for PEEK, heating via a support plate increases heat input and reduces the cooling rate [19]. These findings indicate that pin shoulder configuration and heat control settings must be considered in the welding process. However, improvements in surface quality or changes in crystallinity cannot serve as the sole indicators of joint success. The evaluation must be supplemented with mechanical testing, internal defect inspection, and analysis of the relationship between thermal conditions and the structure of the weld zone.

Overall, previous studies indicate that FSW performance in 3D-printed polymers is influenced by the interaction between process parameters, infill density and pattern, pin geometry, material characteristics, and thermal condition control. Various studies have shown that specific configurations can yield promising joint strength or efficiency. However, differences in polymer types, welding equipment, internal design, joint configurations, and testing methods limit the generalizability of results across studies. Furthermore, tensile strength, flexural load, hardness, structural homogeneity, and surface quality represent distinct performance aspects and should not be treated as interchangeable indicators. Therefore, further research needs to combine mechanical testing with morphological and defect characterization in the joint region, while also evaluating the interactions between process parameters, pin geometry, and the internal design of the components. This approach is necessary to elucidate bond formation and determine FSW conditions that align with the material characteristics and application requirements of 3D-printed polymers.

2.2 Friction stir spot welding

FSSW is a friction-based joining technique that uses mechanical stirring to form a joint at a specific location, as illustrated in Figure 2. Unlike continuous FSW, which produces a joint along the entire path of the pin, FSSW forms a localized joint by applying pressure with a rotating pin to the joint area, stirring the material for a specific duration, and withdrawing the pin once the process is complete. The pin's compressive and rotational forces generate heat through friction and mechanical deformation, causing the thermoplastic matrix to soften and allowing the material to flow around the joint zone. After the pin is withdrawn, a hole or keyhole may remain at the pin penetration site. In 3D-printed thermoplastic components, the success of this process depends on adequate softening, flow, and consolidation of the material, as well as defect control in the joint area [20].

FSSW performance depends on cutter rotation speed, penetration rate (plunge rate), penetration depth, mixing time, and pin geometry. These factors affect heat generation, material movement, and joint-zone characteristics. In 3D-printed glass-fiber-reinforced polylactic acid (PLA-GF) composites, the highest tensile-shear strength of 930.7 N was obtained at a rotational speed of 900 rpm and a plunge rate of 20 mm/min. Meanwhile, the highest flexural strength of 293.7 N was achieved at a rotational speed of 2,100 rpm and a plunge rate of 30 mm/min [20]. These differing

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conditions indicate that the parameters yielding the highest tensile-shear strength do not necessarily provide the best flexural response. The study also showed that the effect of rotational speed depends on the plunge rate; therefore, both parameters must be evaluated simultaneously. These results apply to the PLA-GF configuration and the range of parameters tested, not as universal optimal conditions for all thermoplastic materials.

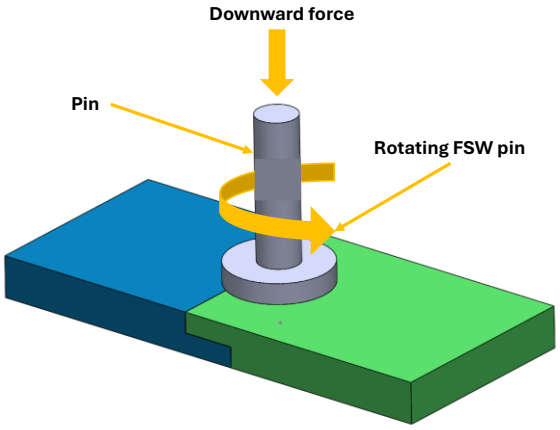


Figure 2. Schematic of the FSSW operating principle

The influence of process parameters on joint performance was also observed in PLA-PEKK-HAp-CS composite scaffolds produced via FFF printing. A combination of a rotation speed of 1,000 rpm, a consumable pin depth of 2 mm, and a mixing time of 20 seconds was reported to yield the best conditions for strength and surface hardness in that experiment [21]. However, this study aimed to evaluate the feasibility of localized repairs on biomedical scaffolds, not to determine FSSW parameters for structural components in general. Therefore, the results are more appropriately used as evidence that FSSW can be applied to composite thermoplastic structures with specific geometries and functions. Differences in material, porosity, geometry, and intended use also limit direct comparisons between the results of this study and those for PLA-GF.

In addition to process parameters, the characteristics of the joint zone provide important information for explaining variations in mechanical performance. In PLA-GF, three zones were identified after welding: the stir zone, the mixed zone, and the shoulder zone. The shoulder zone forms due to contact between the pin shoulder and the material surface, while the mixed zone exhibits material movement and mixing due to the effects of heat and pin rotation. The stir zone forms in the area that interacts directly with the pin, and a hole may remain after the pin is withdrawn. Defects were found in the joint zones of specimens with relatively lower mechanical performance; further analysis also showed that improper welding conditions can result in voids, uneven mixing, and excessive flash formation [20]. These findings indicate that joint strength cannot be adequately explained solely by process parameter values. Material flow characteristics, consolidation, and defects in each zone must also be considered when evaluating joint quality.

Process modifications using ultrasonic vibration have been investigated to address material flow limitations in the joining of dissimilar polymers. In ultrasonic-assisted friction stir spot welding (UA-FSSW), ultrasonic vibration is introduced into the FSSW process to influence material softening and movement. In the joining of PLA Plus and carbon-fiber-reinforced PLA (PLA-CF), an ultrasonic amplitude of 90% produced the highest joint quality among the tested conditions in a configuration with PLA Plus on top and PLA-CF on the bottom. The reported joint efficiencies reached 57.2% relative to the PLA Plus reference material and 154.4% relative to the PLA-CF reference material. The study also reported improved material flow, fewer interface defects, and a more homogeneous weld zone in this configuration [12]. Nevertheless, UA-FSSW results must be distinguished from those of conventional FSSW because ultrasonic vibration is an additional variable

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in the process. Joint efficiencies above 100% should also be interpreted based on the definition and reference materials used, rather than as evidence that the joint is superior in all mechanical aspects.

Overall, the reviewed studies indicate that FSSW has the potential to be used for joining 3D-printed thermoplastic components, including fiber-reinforced composites and structures with specialized functions [12], [20], [21]. However, differences in material composition, joint configuration, welding parameters, and testing methods limit quantitative comparisons across publications. The available evidence also suggests that improvements in joint strength are inextricably linked to the characteristics of the joint zone and defect formation. Future research needs to link forming and welding parameters to the morphology of the weld zone, defect distribution, and failure modes through complementary mechanical testing and characterization. Consistent reporting of process conditions, definitions of efficiency, and reference materials is also necessary to ensure that results across studies can be compared more reliably.

2.3 Rotary friction welding

RFW, also referred to in some studies as spin friction welding (SFW), is a joining method that uses heat generated by relative friction at the interface between two components under an axial force. In this configuration, one component rotates while the other remains stationary. Friction at the interface generates heat that softens the material around the joint, while the axial force maintains contact and promotes material movement in that area. When the rotation phase ends, the softened material consolidates under pressure, forming a joint. This method has been studied for joining FFF-printed thermoplastic components or extruded materials (MEX), particularly rod- or cylinder-shaped specimens, whether made of the same or different materials [22], [23], [24]. The basic configuration of the joining process, with one specimen rotating and the other stationary under axial force, is shown in Figure 3.

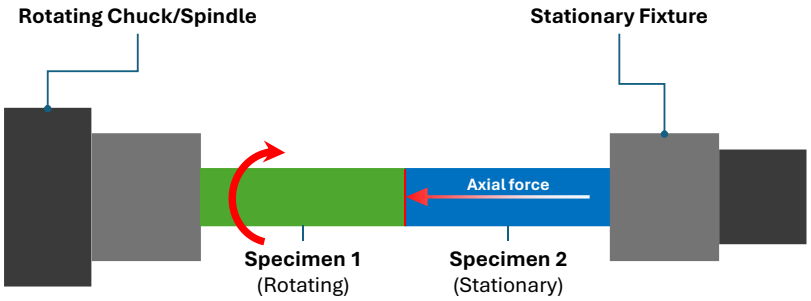


Figure 3. Schematic illustration of the rotary friction welding (RFW) configuration for joining 3D-printed thermoplastic specimens

The application of RFW to FDM-printed thermoplastic components has been studied using various material combinations. One process parameter examined is rotational speed. For rod-shaped specimens joining PLA with PLA, ABS, glass-fiber-reinforced (GF) PLA, carbon-fiber-reinforced (CF) PLA, polycarbonate (PC), or polyamide (PA), increasing the rotational speed from 330 to 1350 rpm increased the impact energy and flexural strength of the joint in the tested material combinations. The magnitude of the increase varied by material pair, while the surface hardness of the weld zone did not increase proportionally with rotational speed [24]. These results indicate that the effect of rotational speed on joint performance needs to be evaluated based on several mechanical properties.

The effect of rotational speed settings was also reported for PLA rods produced via fused filament fabrication (FFF). Gradually increasing the speed up to 4,000 rpm resulted in an average increase in flexural strength of 41.94% compared to the base PLA material. The surface hardness of the weld interface under the reported test conditions was also approximately 1.25-3.80% higher than that

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of the base material [22]. These findings suggest that rotation speed control strategies are related to joint performance, although their effects must be interpreted based on process conditions and the mechanical properties being tested.

In addition to rotational speed, the combination of materials and temperature conditions also contributes to joint performance. In PLA rods containing metal powder, the flexural strength of the joint between PLA and aluminum-powder-filled PLA increased by approximately 57.5% when the welded components were placed at an ambient temperature of 45 °C [25]. In another study using PLA and ABS rods produced via Material Extrusion (MEX), the material combination and the number of perimeter shells were the most influential factors on joint strength and cylindricity in the ANOVA analysis. The highest joint efficiency of 93.16% was obtained for the PLA/PLA pair under the reported test conditions [7]. For ABS/PC joints, an increase in rotational speed was associated with increased surface hardness, flexural strength, and impact energy within the tested range. In flexural testing, failure primarily occurred in the ABS specimens [26].

In addition to mechanical properties under static loading, the performance of RFW joints has been evaluated through fatigue testing and variations in interface geometry. For ABS/PC joints, fatigue life increased with rising rotational speed under the experimental conditions studied. The fatigue life of these joints was also reported to be higher than that of unjoined ABS and PC specimens [23]. In contrast, the application of a male-female interlocking geometry to 3D-printed PLA joints did not result in an increase in tensile strength. The tensile strength of specimens with interlocking was only about 30% of that of the control specimens. These results are attributed to the accumulation of weld flash in the interlocking region, which restricts material flow and increases stress concentration, potentially triggering crack initiation [27].

Overall, these studies indicate that the performance of RFW joints in thermoplastic components produced via FDM/FFF is related to rotational speed, material combinations, testing conditions, and interface geometry. Evaluation of the joints must therefore consider mechanical properties relevant to the application, such as flexural or tensile strength, impact energy, hardness, and fatigue life. Furthermore, because the studies discussed used rod- or cylinder-shaped specimens, applying the results to components with more complex geometries requires considering differences in specimen shape and process conditions.

2.4 Ultrasonic welding

Ultrasonic welding is a thermoplastic joining method that utilizes high-frequency mechanical vibrations to generate heat at the interface between two components. Electrical energy is converted into mechanical vibrations by a transducer, then transmitted through a booster and a sonotrode (horn) to the specimens, which are positioned in an overlapping configuration and subjected to compressive force. Heat is generated through interfacial friction and viscoelastic dissipation within the polymer, causing the material to soften or melt in the joint area. After the vibrations stop, pressure is maintained during cooling until the joint is formed [28], [29], [30]. The equipment configuration and operating principle of ultrasonic welding, including the position of the energy director that helps focus energy on the joint area, are shown in Figure 4.

An energy director (ED) is a geometric feature at the joint interface that concentrates ultrasonic energy and helps initiate melting at the contact area. In 3D-printed components, the ED can be directly integrated into the specimen design. The ED shapes studied include mesh and circular patterns on PEEK and short-fiber-reinforced PEEK (CF-PEEK) [28], triangular, semicircular, and cross shapes in FDM-printed PLA specimens [29]; and rectangular, semicircular, and triangular shapes in extrusion-printed ABS and PLA components [29], and rectangular, semicircular, and triangular shapes in extrusion-printed ABS and PLA components [30]. In PLA specimens, the cross-

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shaped ED (cross energy director, CED) produced higher joint strength compared to the triangular and semicircular EDs under certain test conditions. However, the CED also exhibited higher thermal degradation and flash formation around the weld zone under certain welding conditions [29]. Thus, an increase in the ED's ability to concentrate energy does not always result in a better joint in all aspects.

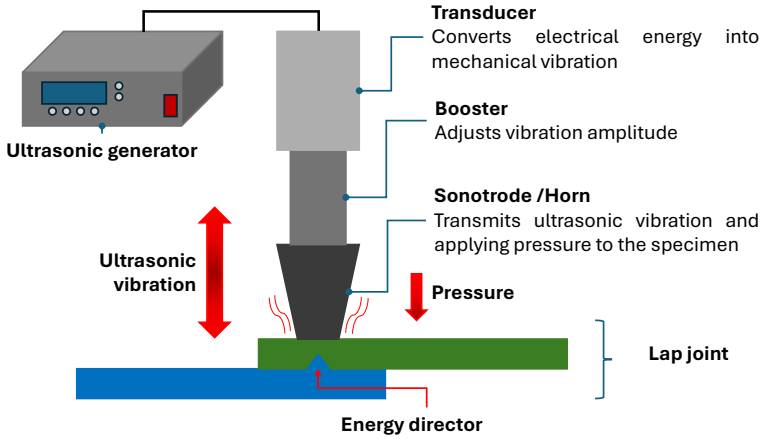


Figure 4. Schematic of the equipment and operating principle of ultrasonic welding on polymer components using an energy director

In addition to ED geometry, joint quality is influenced by amplitude, welding time, energy, and clamping force. In PEEK and CF-PEEK welding, amplitudes of 30 and 40 µm, as well as ED shape, affect process characteristics, including welding duration and joint response. An amplitude of 40 µm resulted in a shorter welding time under the energy conditions studied, but the effect of the ED shape differed between PEEK and CF-PEEK. Therefore, these results cannot be simplified into the conclusion that a higher amplitude always produces higher joint strength [28]. Meanwhile, testing on PLA showed that increasing welding parameters to medium and high levels can lead to greater joint degradation, particularly in specimens with cross-shaped EDs [29]. These findings indicate that welding parameters should be adjusted based on material characteristics and ED design to achieve strong joints without increasing the risk of thermal degradation.

The type of polymer and the internal structure of the 3D-printed parts also influence joint quality. In ABS/ABS, ABS/PLA, and PLA/PLA hybrid welding, the material combination was the most influential factor on the shear strength and elongation of the joints in the experimental design used, followed by the infill percentage and ED shape. Welding time and amplitude were also evaluated, but their effects depended on the experimental conditions [30]. In PLA specimens, 100% infill produced higher interfacial heat compared to 80% and 90% infill, but it also caused greater thermal degradation [29]. These results indicate that conditions that enhance material strength prior to welding do not necessarily reduce degradation during welding. Therefore, infill settings must account for the component's initial condition and its thermal response during the joining process.

Joint performance was evaluated based on mechanical strength, joint efficiency, and failure characteristics. For PEEK and CF-PEEK, the effect of welding amplitude on joint failure force depends on the material type and ED geometry [28]. Meanwhile, most ABS/ABS and ABS/PLA joints exhibit delamination-type fracture in the overlap region, whereas most PLA/PLA joints exhibit adherent-type fracture [30]. These differences in fracture patterns indicate that the material combination is related to the failure characteristics of the joint. Therefore, evaluating joint quality requires more than just mechanical strength and joint efficiency; it must also consider the location and characteristics of the fracture. Overall, the success of ultrasonic welding on 3D-printed polymer components depends on selecting process parameters and ED geometry appropriate for

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the polymer type and the internal structure of the printed part, while taking into account joint strength and the risk of thermal degradation under the applied experimental conditions.

2.5 Laser joining

Laser joining is a thermoplastic joining method that utilizes laser energy to generate localized heating at the interface of two components arranged in an overlap configuration. In a transmission configuration, the laser beam passes through a component that is relatively transparent to the laser wavelength and is absorbed by the mating component, which has higher absorptivity. This energy absorption generates heat at the interface, causing the material to soften or melt and form a bond after cooling and solidification. This principle has been applied to FDM-printed PLA components using a ytterbium fiber infrared laser system [31]. Other research has evaluated the use of diode lasers to join FDM-produced PLA components via an overlapping configuration [11]. A schematic of the operating principle of laser joining for FDM-produced PLA components is shown in Figure 5.

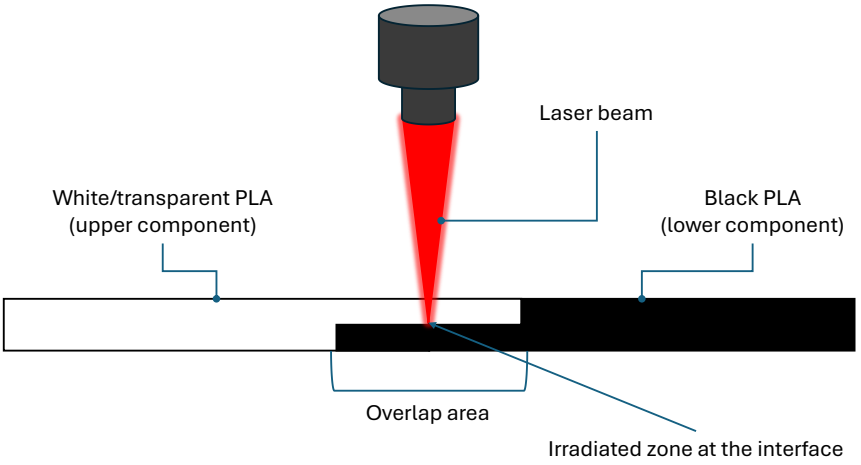


Figure 5. Schematic illustration of the laser joining principle for overlapping FDM-printed PLA components

The quality of laser joints in FDM-fabricated components is influenced by irradiation conditions and the optical characteristics of the materials. For colorless and black PLA pairs, the pulse energy density was varied to evaluate the tensile strength of the joints using a 20 W ytterbium fiber infrared laser [31]. For a pair of white and black PLA, variations in laser power from 100 to 200 W and interaction times from 7 to 13 s resulted in energy densities of 3.48-12.93 J/mm². Shear strength exceeded 10 MPa at energy densities of 3.48-8.5 J/mm², but decreased at 12.93 J/mm² due to cohesive failure in the PLA material and surface deformation [11]. These findings indicate that increasing laser energy does not always improve joint strength.

2.6 Microwave-assisted welding

Microwave-assisted welding utilizes microwave energy to join 3D-printed thermoplastic components through localized heating with the aid of an absorbent material placed at the joint interface. During the process, the components are positioned on a support structure and exposed to microwaves generated by a magnetron. The absorbent material interacts with the microwave energy and generates heat at the joint area, thereby promoting localized softening or melting of the thermoplastic material and enabling the formation of a bond between the components. The operating principle and conceptual diagram of the microwave-assisted welding configuration for 3D-printed components are shown in Figure 6.

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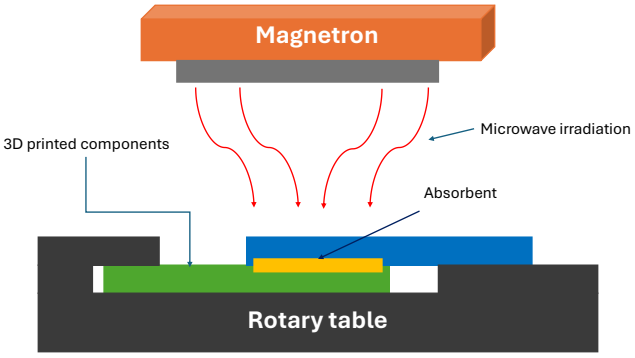


Figure 6. Schematic illustration of the microwave-assisted welding setup for 3D-printed thermoplastic components

Microwave-assisted welding has been studied on components made of acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) produced via material extrusion additive manufacturing (MEX-AM) to overcome the limitations of the build bed size in 3D printers. The study used Fe_2O_3 as the microwave energy-absorbing material. The parameters studied included microwave power, mass of the absorber material, compressive load, material combinations, and infill percentage. In preliminary feasibility experiments, joints were successfully formed without damage within a microwave power range of 600-1000 W, an absorber material mass of 0.2-0.3 g, and a compressive load of 400-1200 g. This range was used as the basis for determining parameter levels in subsequent experiments [13].

3. Comparative synthesis and research challenges

3.1 Comparative synthesis of welding techniques

The six welding techniques reviewed have different joint formation mechanisms and process requirements. FSW and FSSW rely on friction and mechanical deformation to soften and consolidate the material in the joint area. RFW , utilizes friction resulting from the relative rotational motion between two components subjected to an axial force. Meanwhile, ultrasonic welding produces localized heating through high-frequency mechanical vibrations, whereas laser joining uses radiant energy to heat the interface. In microwave-assisted welding, heating is achieved through the interaction of microwaves with an energy-absorbing material placed in the joint area. These differences in mechanisms determine the process parameters that need to be controlled and the characteristics of the resulting joints.

The influence of process parameters also varies among techniques. In FSW and FSSW, rotational speed, welding speed or penetration rate, tool geometry, and infill conditions play a role in heat generation and material flow [8], [15], [20]. In RFW, rotational speed interacts with the combination of materials and forming conditions, including the number of perimeter shells [7], [24]. In ultrasonic welding, amplitude, welding time, contact force, and the geometry of the energy director influence energy concentration and bond formation [28], [29], [30]. In laser joining, the power and irradiation time determine the energy density received at the interface, while differences in the optical characteristics of the two components affect the absorption of laser energy [11], [31]. In microwave-assisted welding, microwave power, the mass of the absorbent material, joining pressure, and material combinations are the factors studied in joint formation [13].

A comparison of research results shows that increasing energy input or process intensity does not always result in improved joint performance. In FSW, the effects of infill density and pin geometry indicate that material availability and mixing capability must be considered alongside process parameters. In ultrasonic welding, increasing welding parameters can exacerbate thermal degradation under certain conditions, particularly when energy is concentrated at the energy

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director [29]. In laser joining, an increase in energy density is not always accompanied by a proportional increase in shear strength; at high energy inputs, the measured strength may decrease when the specimen experiences cohesive failure in PLA material, accompanied by surface deformation [11]. For microwave-assisted welding, the available research primarily demonstrates the initial feasibility of joining MEX-printed components; this evidence is not yet sufficient to establish a general relationship between energy input and joint performance across various material types. Thus, appropriate process conditions must be determined based on a balance between bond formation, thermal damage, and the targeted mechanical properties.

A comparison of mechanical performance among these techniques must also be conducted with care. The reviewed studies employed a variety of material types, specimen geometries, joint configurations, and testing methods. For example, tensile strength in FSW, tensile-shear force in FSSW, flexural strength in RFW, and shear strength in laser joining are different indicators. The results reported for microwave-assisted welding also need to be interpreted based on the experimental configuration and the performance indicators used. The joint strength or efficiency values from these tests cannot be used directly to determine the most superior technique. Comparative evaluation requires comparable test conditions and consistent performance definitions.

3.2 Research challenges and directions for development

One of the main challenges is the interrelationship between welding parameters and the internal characteristics of 3D-printed components. Raster orientation, density and infill patterns, the number of perimeter shells, and porosity can all influence material distribution and bond formation. The effects of these factors are not always the same across all techniques. Therefore, future research needs to integrate printing parameters and welding parameters into the experimental design so that the contribution of each factor and their interactions can be more clearly identified.

The next challenge is controlling damage and defects in the joint area. Inappropriate heat input can cause thermal degradation, deformation, inadequate consolidation, or the formation of internal defects. Furthermore, the accumulation of weld flash in RFW and cohesive failure in laser joining indicate that joint quality is determined not only by bond formation but also by material changes around the interface. In microwave-assisted welding, the distribution of the absorbent material and local heating also need to be evaluated to ensure joint formation without excessive damage to the components. Joint evaluation must therefore combine mechanical testing with morphological observations, defect identification, and analysis of failure locations and mechanisms.

Another limitation lies in the lack of uniformity in approaches to evaluating joint performance. The reviewed studies used a variety of loading types, reference materials, and definitions of joint efficiency. These conditions limit quantitative comparisons across publications and make it difficult to determine the most generally effective parameters. The use of more consistent testing protocols, comprehensive reporting of joint dimensions and configurations, and the presentation of variations in measurement results will help improve the comparability and reproducibility of the research.

In addition, some studies use relatively specific specimens and joint configurations, such as cylindrical rods in RFW or lap joints in laser joining and ultrasonic welding. Evidence for microwave-assisted welding on separately cast components is also still limited compared to some of the other techniques reviewed. Results from these configurations may not necessarily apply directly to components with complex geometries, varying thicknesses, or operational loading conditions. Further research is needed to test the applicability of these welding techniques on components that are more representative of real-world applications, including evaluating the strength, reliability, and stability of joints under relevant usage conditions.

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Based on this synthesis, the development of welding for FDM/FFF-printed thermoplastic components requires an integrated approach that links printing parameters, welding mechanisms, structural formation and defects, and mechanical performance. The research priority is not only to identify process conditions that yield the highest strength for a single configuration but also to elucidate the process-structure-property relationship so that the results can be interpreted, reproduced, and applied to a wider range of materials and component geometries.

4. Conclusion

This review evaluates six welding techniques for joining 3D-printed thermoplastic components: friction stir welding (FSW), friction stir spot welding (FSSW), rotary friction welding (RFW), ultrasonic welding, laser joining, and microwave-assisted welding. The findings indicate that each technique has distinct joint formation mechanisms and process parameters. Joint performance is determined not only by welding conditions but also by material characteristics, the internal structure of the printed parts, joint configuration, and the type of mechanical testing used.

Key findings indicate that increasing process intensity or energy input does not always result in improved joint quality. In friction-based welding, tool geometry and infill characteristics influence material flow and consolidation. In ultrasonic welding, the geometry of the energy director and welding conditions affect interface heating and the risk of thermal degradation. Meanwhile, in laser joining, the optical properties of the materials and the laser energy density play a role in bond formation and the risk of deformation. In microwave-assisted welding, joint formation is also influenced by heating conditions and the use of energy-absorbing materials in the joint area. Therefore, the determination of process parameters must consider a balance between adequate bond formation and the prevention of defects or material damage.

Although various studies demonstrate the potential for applying these techniques, direct comparisons between them remain limited by differences in materials, specimen geometries, joint configurations, testing methods, and reference materials. Results obtained from specific specimen configurations may not necessarily be directly applicable to components with more complex geometries or different operating conditions. Future research needs to integrate printing and welding parameters, characterize the morphology and failure mechanisms of joints, and adopt more consistent testing and reporting methods. These efforts are necessary to clarify the relationship between process parameters, joint structure, and mechanical properties, while improving the reproducibility, reliability, and practical application of 3D-printed thermoplastic component joints.

Author's declaration

Author contribution

Rahmat Azis Nabawi: Conceptualization, Methodology, Resources, Writing - Original Draft, Visualization. **Febri Prasetya**: Formal analysis, Writing - Review & Editing. **Yogi Dial Alfana**: Formal analysis, Writing - Review & Editing. **Dani Harmanto**: Writing - Review & Editing.

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Data availability

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical clearance

Not Applicable.

AI statement

The authors declare that no AI tools were used to generate scientific content, research findings, or interpretations in this manuscript. ChatGPT was used solely to assist with language checking and improving readability. The manuscript was also proofread by an English language expert. The authors take full responsibility for the accuracy and content of the article.

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References

[1] Mhd. F. M. Putra, S. Syahril, and D. Y. Sari, "Mechanical characteristics and FEA-based non-uniform infill density approaches for Fused Deposition Modelling (FDM)-printed components: A literature review," *Journal of Engineering Researcher and Lecturer*, vol. 5, no. 2, 2026, https://doi.org/10.58712/jerel.v5i2.220

[2] M. Q. Hanif, R. Rifelino, F. Prasetya, and Z. Abadi, "Adhesion mechanisms and mechanical performance of single-lap joints in FDM-3D printed: A review," *Journal of Engineering Researcher and Lecturer*, vol. 5, no. 1, 2026, https://doi.org/10.58712/jerel.v5i1.214

[3] S. C. Altıparmak, V. A. Yardley, Z. Shi, and J. Lin, "Extrusion-based additive manufacturing technologies: State of the art and future perspectives," *Journal of Manufacturing Processes*, vol. 83. 2022. https://doi.org/10.1016/j.jmapro.2022.09.032

[4] Z. Jiang, B. Diggle, M. L. Tan, J. Viktorova, C. W. Bennett, and L. A. Connal, "Extrusion 3D Printing of Polymeric Materials with Advanced Properties," *Advanced Science*, vol. 7, no. 17. 2020. https://doi.org/10.1002/advs.202001379

[5] D. Anggara, R. Rifelino, Z. Abadi, and A. Arafat, "Exploring how 3D printing parameters affect the flexural strength of ABS materials," *Innovation in Engineering*, vol. 1, no. 2, pp. 125–133, Sep. 2024, https://doi.org/10.58712/ie.v1i2.16

[6] S. Palaniyappan, N. K. Sivakumar, M. Bodaghi, M. Kumar, and M. Rahaman, "A feasibility study of various joining techniques for three-dimensional printed polylactic acid and wood-reinforced polylactic acid biocomposite," *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 238, no. 3, 2024, https://doi.org/10.1177/14644207231189956

[7] V. K. Tiwary, A. P., and V. R. Malik, "Investigations on the effect of Spin Friction Welding parameters on joint strength and cylindricity of similar/dissimilar Material Extrusion (MEX)

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3D printed parts," *Journal of Advanced Joining Processes*, vol. 9, 2024, https://doi.org/10.1016/j.jajp.2024.100208

[8] S. M. Senthil and M. B. Kumar, "Effect of tool rotational speed and traverse speed on friction stir welding of 3d-printed polylactic acid material," *Applied Science and Engineering Progress*, vol. 15, no. 1, 2022, https://doi.org/10.14416/j.asep.2021.09.002

[9] V. K. Tiwary, A. P, and V. R. Malik, "An overview on joining/welding as post-processing technique to circumvent the build volume limitation of an FDM-3D printer," *Rapid Prototyping Journal*, vol. 27, no. 4. 2021. https://doi.org/10.1108/RPJ-10-2020-0265

[10] J. A. Almazán, M. Á. Almazán, M. M. Marín, A. García-Domínguez, and E. M. Rubio, "Mechanical Performance of FDM-Printed PLA Joined by Portable Friction Stir Welding: Influence of Infill Density and Tool Pin Geometry," *Polymers (Basel).*, vol. 18, no. 9, 2026, https://doi.org/10.3390/polym18091013

[11] M. Panico, S. Genna, A. Langella, and I. Papa, "Laser joining of FDM-printed PLA components: feasibility and thermo-mechanical analysis," *International Journal of Advanced Manufacturing Technology*, vol. 139, no. 5–6, 2025, https://doi.org/10.1007/s00170-025-16036-2

[12] E. Baysal, "Investigation of the weldability of 3D printed dissimilar materials (PLA Plus and PLA CF) using ultrasonic assisted friction stir spot welding," *Mater. Today Commun.*, vol. 51, 2026, https://doi.org/10.1016/j.mtcomm.2026.114707

[13] V. K. Tiwary, A. P., and V. R. Malik, "Investigations on microwave-assisted welding of MEX additive manufactured parts to overcome the bed size limitation," *Journal of Advanced Joining Processes*, vol. 7, 2023, https://doi.org/10.1016/j.jajp.2023.100141

[14] N. Vidakis, M. Petousis, A. Korlos, N. Mountakis, and J. D. Kechagias, "Friction Stir Welding Optimization of 3D-Printed Acrylonitrile Butadiene Styrene in Hybrid Additive Manufacturing," *Polymers (Basel).*, vol. 14, no. 12, 2022, https://doi.org/10.3390/polym14122474

[15] O. Koçar, N. Anaç, and E. Baysal, "A New Approach in Part Design for Friction Stir Welding of 3D-Printed Parts with Different Infill Ratios and Colors," *Polymers (Basel).*, vol. 16, no. 13, 2024, https://doi.org/10.3390/polym16131790

[16] S. F. Raza, M. Umair Furqan, S. A. Khan, K. H. Mughal, E. U. Haq, and A. M. Mehdi, "Comprehensive Insights into Friction Stir Butt Welding (FSBW) of 3D-Printed Novel Nano Chromium (Cr) Particles-Reinforced PLA Composites," *Journal of Composites Science*, vol. 10, no. 2, 2026, https://doi.org/10.3390/jcs10020072

[17] G. Şahin, N. Anaç, and O. Koçar, "Investigation of the Weldability of 3D-Printed Multi-Material Materials (PLA and PLA Wood) Using Friction Stir Welding," *Polymers (Basel).*, vol. 16, no. 23, 2024, https://doi.org/10.3390/polym16233249

[18] M. Petousis, N. Mountakis, and N. Vidakis, "Optimization of hybrid friction stir welding of PMMA: 3D-printed parts and conventional sheets welding efficiency in single- and two-axis welding traces," *International Journal of Advanced Manufacturing Technology*, vol. 127, no. 5–6, 2023, https://doi.org/10.1007/s00170-023-11632-6

[19] P. Rendas, L. Figueiredo, P. Melo, C. Galhano, C. Vidal, and B. A. R. Soares, "Investigation of Friction Stir Welding of Additively Manufactured Biocompatible Thermoplastics Using Stationary Shoulder and Assisted Heating," *Polymers (Basel).*, vol. 16, no. 13, 2024, https://doi.org/10.3390/polym16131897

[20] E. Kanlı, O. Koçar, and N. Anaç, "An Investigation into the Friction Stir Spot Welding Behavior of 3D-Printed Glass Fiber-Reinforced Polylactic Acid," *Polymers (Basel).*, vol. 18, no. 9, 2026, https://doi.org/10.3390/polym18091041

[21] R. Singh, J. Singh, G. Singh, and R. Kumar, "Friction Stir Spot Welding of PLA-PEKK-HAp-CS Based 3D Printed Scaffolds for Minor Repair," *Journal of the Chinese Society of Mechanical Engineers*, vol. 41, no. 5, pp. 639–646, 2020, [Online]. Available: https://journal.csme.org.tw/download/Friction-Stir-Spot-Welding-of-PLA-PEKK-HAp-CS-Based-3D-Printed-Scaffolds-for-Minor-Repair.pdf

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[22] C. C. Kuo, H. X. Liang, S. H. Huang, and S. F. Tseng, "Enhancing the Weld Quality of Polylactic Acid Biomedical Materials Using Rotary Friction Welding," *Polymers (Basel).*, vol. 16, no. 7, 2024, https://doi.org/10.3390/polym16070991

[23] C. C. Kuo, H. W. Chen, and S. H. Huang, "Rotary Friction Welding of Dissimilar Polymer Rods Containing Metal Powder," *Polymers (Basel).*, vol. 15, no. 22, 2023, https://doi.org/10.3390/polym15224354

[24] C. C. Kuo, H. W. Chen, J. Y. Xu, C. H. Lee, and S. H. Hunag, "Effects of Rotational Speed on Joint Characteristics of Green Joining Technique of Dissimilar Polymeric Rods Fabricated by Additive Manufacturing Technology," *Polymers (Basel).*, vol. 14, no. 22, 2022, https://doi.org/10.3390/polym14224822

[25] C. C. Kuo, N. Gurumurthy, and S. H. Hunag, "Fatigue Behavior of Rotary Friction Welding of Acrylonitrile Butadiene Styrene and Polycarbonate Dissimilar Materials," *Polymers (Basel).*, vol. 15, no. 16, 2023, https://doi.org/10.3390/polym15163424

[26] C. C. Kuo, N. Gurumurthy, H. W. Chen, and S. H. Hunag, "Mechanical Performance and Microstructural Evolution of Rotary Friction Welding of Acrylonitrile Butadiene Styrene and Polycarbonate Rods," *Materials*, vol. 16, no. 9, 2023, https://doi.org/10.3390/ma16093295

[27] F. Al Fathurrahman, F. R. N. Santoso, Erwin, D. Sugiyanto, and J. Pratama, "Limitations of Interlocking Features in Rotary Friction Welding (RFW) of 3D-printed PLA," *Jurnal Rekayasa Mesin*, vol. 21, no. 1, 2026, https://doi.org/10.32497/jrm.v21i1.7419

[28] B. Khatri, M. F. Roth, and F. Balle, "Ultrasonic Welding of Additively Manufactured PEEK and Carbon-Fiber-Reinforced PEEK with Integrated Energy Directors," *Journal of Manufacturing and Materials Processing*, vol. 7, no. 1, 2023, https://doi.org/10.3390/jmmp7010002

[29] R. S. Rana, I. Singh, and A. K. Sharma, "Ultrasonic welding of printed/molded sustainable polymer specimens with energy directors," *Ultrasonics*, vol. 134, p. 107078, Sep. 2023, https://doi.org/10.1016/j.ultras.2023.107078

[30] V. K. Tiwary, P. Arunkumar, and V. R. Malik, "Ultrasonic Welding of Similar/Dissimilar MEX-3D Printed Parts Considering Energy Director Shape, Infill, Welding Time and Amplitude," *Computers, Materials and Continua*, vol. 84, no. 3, 2025, https://doi.org/10.32604/cmc.2025.066129

[31] J. M. Vazquez-Martinez, D. Piñero, J. Salguero, and M. Batista, "Evaluation of the joining response of biodegradable polylactic acid (PLA) from fused deposition modeling by infrared laser irradiation," *Polymers (Basel).*, vol. 12, no. 11, 2020, https://doi.org/10.3390/polym12112479

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