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Review Article

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Joining of Dissimilar Thermoplastic Polymers Using Friction Stir Processing: A Review

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Abstract

Nowadays lightweight thermoplastic materials are widely used in numerous fabricated parts such as of wings, fuselage panels in aircraft industries, automobile panel and lighting systems in automobile industries because of its greater strength-to-weight ratio, anti-corrosion and self-insulating properties. Friction stir joining is a solid-state processing that is highly popular for the joining of the various structured amorphous to semi-crystalline thermoplastics as fusion heat assisted welding methodologies are not often found to be beneficial due to improper thermal properties. Thus, the weldability of dissimilar thermoplastic materials particularly metal to polymers is highly challenging task because of drastic variance in chemical and thermal properties. This paper addresses the review on the joining of thermoplastic materials in several joint configurations like end to end and overlap using advanced friction stir techniques. The parametric interaction effects using different rotating tool pin geometry on weld bead profile, its interface microstructure extended to joint mechanical behaviour during tensile, impact, and fatigue loading for various unlike base materials have been summarized. Various modified process technologies like preheating of unlike high-density polyethylene (HDPE) to Polyamide-6 laminate, adjusted tool tilting with high plunging depth for thin polymethyl methacrylate (PMMA) to polycarbonate sheet, and threaded cylindrical or square tool pin for polypropylene to polyethylene are indicated case wise. The friction welding process monitoring using different sensors'-based algorithms in the time-frequency domain has also been reviewed. Thus, the process dynamics in real-time are abridged with acquired force, torque, and acoustic signals. This brief review will have a considerable impact on the industrial and manufacturing sectors.

Keywords

Friction stir processing, Thermoplastic polymer, Weld strength, Process monitoring

Introduction

The friction stir processing (FSP) methods are frictional heat-assisted procedures mainly used for surface modifications of low melting point materials (such as thermoplastics), which are difficult to weld by the fusion bead-on-plate processes [1-3]. FSP can preserve microstructural modification with plastic deformation and material mixing along the weld interface. Thus, the mechanical properties of the friction-stirred surface are often found to be improved. Friction stirred processes are also environment-friendly without any toxic gas generation. Thus, FSP is also applied for enhancing the surface microstructure of metallic materials [4, 5], but in recent years some works proposed on FSP for polymeric material by adding different nano powder to increase the weld strength [6-8]. The friction stir welding (FSW) is another variation of FSP to join different low melting point materials [2, 3]. Thus, FSW is a solid-state joining technique generally used to join different light weight non-ferrous materials as well as dissimilar thermoplastics as these base materials' combinations are often difficult to join by the fusion welding methods [9, 10]. However, thermoplastics are widely used in many engineering fields like aerospace and automotive sectors due to their higher strength to weight ratio and self-insulating properties [1-3, 6, 7]. The friction stir welding is an advanced welding technique to join the base materials without melting their interface.

It was first designed by 'The Welding Institute', UK in 1991. Here, the rotating tool pin first plunged into the base materials followed by shoulder of the tool. However, the heat is generated primarily by the friction over the rotating tool to clamped base plates which soften the work interface. The tool pin followed by the shoulder smoothly extrudes on the overlapped base materials due to an axial thrust termed as plunging phase. Thereafter, the rotating tool is traversed along overlapping areas at a specific speed (welding speed) [9, 10] as illustrated schematically in case of welding of dissimilar thermoplastic sheets (Figure 1).

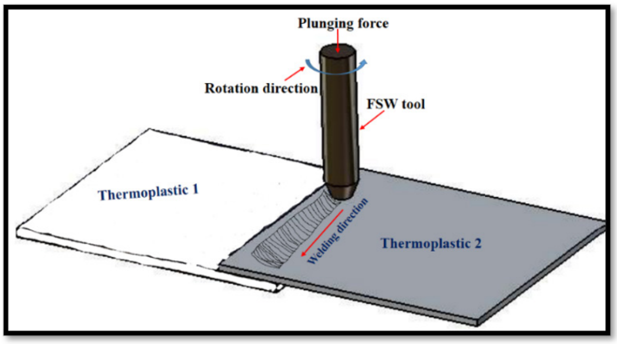

Figure 1: Schematic diagram of friction stir lap welding with tool (dissimilar thermoplastics).

The primary process parameter like tool rotating speed, welding speed are highly influenced the welding strength and bead profile. The joint strength of polycarbonate is further improved (above 10%) than Nylon-6, when the tool revolving speed and traverse speed are 1800 rpm and 20 mm/min respectively in butt configuration [11]. However, weld bead is somewhat uniform at a relatively lower tool rotational speed (1300 rpm) and higher welding speed (60 mm/min) using FSW of polycarbonate to metallic 6061 aluminium alloy in partial over lapped position [9]. The design and selection of tool pin shape is highly crucial for the expansion of weld quality aspects especially for the friction stir welding of thermoplastic polymers. Most of works the cylindrical, taper and cylindrical threaded tool pin have been proposed for the friction stirred joining of dissimilar thermoplastics polymers [9-11].

Literature Review

In past few years, several base materials combinations in different configurations such as metal to metal, polymer to polymer and metal to polymer are investigated using FSW as summarized in the following subsections. However, recent joining issue is mainly addressed on dissimilar thermoplastics weld due to their light weight and inherently insulted properties. From the preceding FSW studies, it is observed that primary process parameters like as tool revolving speed, welding speed and tool geometry and its materials have a major effect on joint strength and weld bead profiles. Friction stirred processing have been tested in thick butt and overlapped thin sheets spot and lap configurations in numerous experimental studies.

Metal to metallic materials joining using FSW

The tool stirring speed and its feed rate are the crucial process variables in friction stirring processes. However, the tilt angle of revolving tool extensively affects the lap joint shear strength using FSW of metallic AA6061-T6 aluminium alloy [12]. Zheng et al. [13] conducted feasibility tests on dissimilar aluminium alloy to nickel alloy and found that, the plunging depth of the tool up to 0.3 mm with intermediate axial load (7.9 kN) increases the weld strength keeping tool rotating speed and welding speed constant at intermediate range. Conversely, the intermetallic reaction at weld interfaces is highly influenced the weld strength of dissimilar non-ferrous Al 6061-T6 aluminium alloy to ferrous ultra-low carbon steel as reported by Helal et al. [14]. The joining of thick metallic 6061 aluminium alloy using friction stir welding can be monitored using the time-frequency wavelet analysis of acoustic emission signals.

Thermoplastic to thermoplastic polymers joining using FSW

The thermoplastic materials are characterized by low melting point with low thermal conductivity that indicates its difficulty to develop joint by fusion welding techniques. Thus, several efforts have been made using friction based stirred processes to achieve desired weld quality. The FSP of PMMA was proposed by adding alumina nanoparticle powder to the base material, which results in an increase in hardness, tensile strength, and flexural strength of base material [6]. However, at higher rotational speed (1600 rpm), there is a uniform graphite distribution was noticed in HDPE weld using FSP [7]. The tensile strength of friction stirred high density polyethylene can be improved with addition of filler material of Fe-Fe_3O_4 powder, at low tool revolving speed (630 rpm) with tool tilt angle (2 degree) [8]. Mert et al. [15] performed friction stir welding of polypropylene sheets with three overlapping configurations to compare the joint strength. The highest weld strength was achieved by the hybrid procedure of friction stir spot welding with adhesive bonding. Arici et al. [16] conducted experiments on polyethylene sheets by taking H13 tool steel as tool material having cylindrical pin. The interface effect of tool tilt angle and joining speed was found to be significant on tensile shear strength of the weld joint. Pirizadeh et al. [17] is proposed a newly modified self-reacting type of tool having two shoulders that traces both upper and beneath the surface of base plates. The tool pin shape was also established to be crucial on the joint strength.

Derazkola et al. [18] studied the influence of tool rotating speed, tilt angle and plunge depth on polycarbonate lap weld strength. The weld strength was found to be drastically improved at an intermediate range of each process parameter. In contrary, a degree of preheating of base materials can enhance the dissimilar HDPE to polyamide weld strength using FSW [19]. This base plate preheating was also found to be beneficial to improve bonding strength of the HDPE sheets welds in butt configuration [20]. Kumar et al. [21] suggested the cylindrical threaded pin for the joining of dissimilar thermoplastics. It was observed that the joint strength efficiency increases with higher tool rotational speed up to a certain extent essentially due to improved frictional heat input along the tool-work interface. Dashatan et al. [22] scrutinized the feasibility of FSW process for the dissimilar poly methyl methacrylate to acrylonitrile butadiene styrene sheets. Here, the dwell time was found to be ominously influenced the weld quality.

Conversely, the cylindrical pin is often found to be suitable for some specific thermoplastic materials such as polylactic acid sheets even in butt alignment by using FSW [23]. However, the influence of pin geometry at different parametric settings was also affected on join quality features. Whereas the cylindrical threaded pin contour is highly effective for the joining of glass filled Nylon-6 composite sheets using FSW. The weld tensile strength improves with a surge in frictional heat input and adequate material moving by the rotational tool along the joint interface [24]. This threaded cylindrical pin profile also found to be superior for high density polyethylene sheets using FSW when dwell time is somewhat higher [25]. This threaded pin contour is further used for the joining of dissimilar thermoplastics polymers namely polypropylene and polyethylene sheets that again indicated the similar improvements over cylindrical tool pin on the weld shear strength [26]. However, conical tapered pin profile can significantly increase the weld strength in case of ABS sheets as base materials [27]. Ahmadi et al. [28] proposed Taguchi method for the parametric optimization of FSW process to achieve the maximum joint strength for 4 mm thick polypropylene composite sheets with 20 wt% carbon fiber. The result indicated that the tensile-shear strength can be improved up to 6.06 MPa at slight inverted position (1 degree) of revolving tool when welding speed and rotational speed were at intermediate range (25 mm/min and 1250 rpm, respectively). The thermoplastic weld quality characteristic can also be monitored using axial thrust with associated stirring torque fluctuation during welding phase. Sahu et al. [11] developed joint strength equation using root mean square of thrust and torque in response surface models for the prediction of Nylon-6 as well as polycarbonate weld bead quality in friction stir butt welding. Thus, the weld ductility can also be improved by using the statistical features of thrust-torque combinations in the fracture elongation models. In this work a comparative assessment was made in terms of the weld bead macrograph, weld micro-hardness, stress-elongation graph between the strongest and weakest joints as shown in figure 2. The weld bead was somewhat uniform using cylindrical pin. Whereas the weld reinforcement was higher at high turning speed (2600 rpm) and high cross speed (30 mm/min) as shown in figure 2a. The hardness of weld also higher at lower welding speed (20 mm/min) for both polycarbonate and Nylon-6 as shown in figure 2b. However, the joint tensile strength was significantly enhanced in higher rotational speed (1800 rpm) using cylindrical pin as presented in figure 2c.

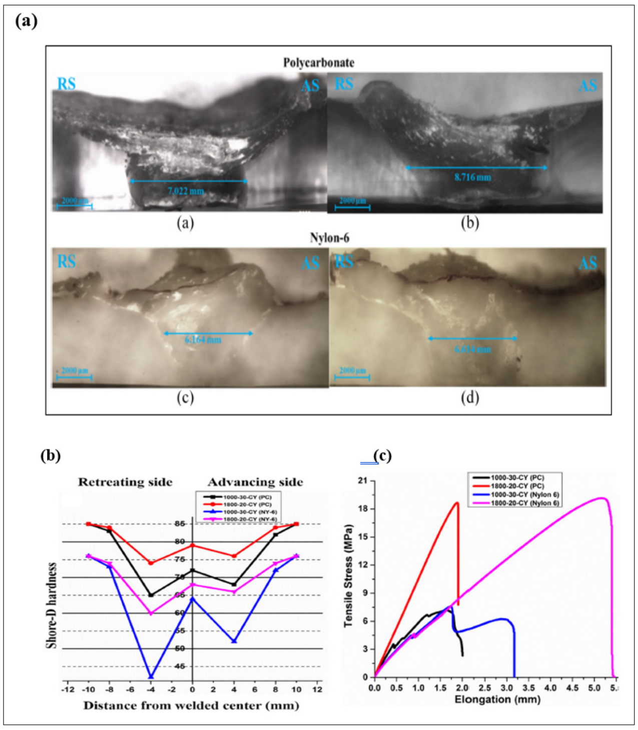

Figure 2: (a) Weld bead macrograph of strongest and weakest joint: (a) 1000 RS – 30 TS – cylindrical pin (PC), (b) 1800 RS – 20 TS – square pin (PC), (c) 2600 RS – 30 TS – triangular pin (N6), and (d) 1800 RS – 20 TS – square pin (N6) [11]. **(b)** Variation of weld micro-hardness for strongest and weakest joint using cylindrical tool pin [11]. **(c)** Stress-elongation diagram for strongest and weakest joint using cylindrical tool pin [11].

Metal to thermoplastic materials joining using FSW

Several attempts have also been made for the drastic difference in thermal properties like dissimilar metallic to thermoplastic materials joining using friction stirred processing. Wilkins et al. [1] proposed friction stir welding lap welding for thin 6061 aluminium alloy and high-density polyethylene. The weld-interface was further treated with friction stir processing again to modify the microstructure. However, the investigation revealed an improvement of thermal and electrical conductivity of the surface over base high-density polyethylene material. Lambaise et al. [29] studied parametric effects for the aluminium to PVC polymer sheets by taking higher axial load (320 N) with higher dwell time (20 s) to achieve the highest joint strength though the surface roughness of the weld profile is relatively poor. The tungsten carbide tool is also considered over tool steel as tool material to improve the friction stir lap welding of Al-Mg alloy to PMMA sheets with great success due to improved mechanical interlocking without any defect along the dissimilar interface [30].

The taper threaded pin with triple facets (concave shoulders) can enhance the unlike metallic Al6061 alloy to PEEK (polyether ether ketone) using FSW [31]. It was observed that the mechanical interlocking again plays a vital role on weld quality in terms of joint strength and weld hardness. The hardness value of the stirred zone is relatively higher than the base material PEEK due to the presence of Al particle in the stirred zone. However, the axial thrust and corresponding torque during plunging and welding plays a key role in metal to ther-

Table 1: Summarized assessment on FSW of thermoplastic materials joining.

Author(s)	Work materials	Tool material & pin geometry	Process parameter	Remarks
Arici and Selale [16]	Polyethylene sheets	H13 steel with cylindrical tool pin	Welding speed, Tilt angle	• Tensile test has been conducted in ISTRON 4411 machine with crosshead speed 100 mm/min. • The maximum tensile strength was found on tool tilt angle 1° and welding speed 12.5 mm/min.
Mert and Arici [15]	Polypropylene sheets	H13 steel with cylindrical pin	Dwell time, Tool rotation speed, Plunge depth	• ISTRON 4411 machine used for tensile test. • The maximum joint strength was observed in hybrid joint configuration.
Bilici et al. [25]	High-density polyethylene sheets	H13 steel tool with cylindrical threaded pin	Tool rotational speed, Dwell time, Tool plunge depth	• Tensile test has been conducted in ISTRON machine with crosshead speed 5 mm/min. • The welding strength was better with a rise in dwell time.
Dashatan et al. [22]	Poly-methyl methacrylate and ABS	H13 steel tool with cylindrical threaded.	Tool rotational speed, Welding speed, Dwell time	• Tensile lap shear test has been carried out according to ASTM D1002-05. • Joint strength was increased by an upturn in both tool revolving speed and dwell time. • Joint strength was increased with an increase in dwell time.
Ahmadi et al. [28]	High-density polyethylene sheets	cylindrical threaded and conical grooved pin	Tool rotational speed, Welding speed, Tilt angle	• Taguchi method used for optimization process. • The welding strength decreased with an increase in welding speed after that it increase.
Pirizadeh et al. [17]	ABS sheets	Cylindrical tool with simple pin and convex pin	Tool rotation speed, Welding speed, Pin geometry	• Tensile test has conducted in SANTAM 50 machine with crosshead speed 5 mm/min. • When rotational speed increases tensile strength was decreases.
Sadeghian and Givi [27]	ABS sheet	Cylindrical shoulder with a cylindrical threaded pin and cylindrical shoulder with conical pin	Tool rotational speed, Traverse speed, Tilt angle, Shoulder diameter, Pin diameter	• Tensile test has been carried out in UTM machine. • Maximum welding strength occurred at a 2-degree tilt angle, 25 mm/min, and 900 rpm of rotational speed.
Hajideh et al. [26]	Polyethylene and polypropylene sheets	H13 steel tool with square cylindrical threaded, triangular. Straight cylindrical pin	Tool rotating speed, Welding speed	• Durometer hardness test has been conducted. • Utilizing the tool with a threaded cylindrical pin provides better mechanical properties for the welded joints.
Kumar et al. [24]	Glass-filled Nylon-6 (Polymer matrix composite) sheets	H13 steel tool with cylindrical threaded pin	Tool revolving speed, Welding speed, Tilt angle	• Computerized tansometer used for tensile testing with strain rate 0.5 mm/min. • The joining strength and elongation (in %) of glass-filled Nylon-6 composites improved with a surge in tool rotating speed.
Derazkola et al. [30]	Polycarbonate sheets	HSS steel tool with Frustum Pin	Tool rotation speed, Plunge depth, Tilt angle	• Tensile test has been conducted in transverse test method. • Joint strength rises with a growth in tool rotational speed, plunge depth, and tilt angle and after certain stage, it will decrease.
Kumar et al. [21]	Polyamide 6 and ABS sheets	H13 steel tool with cylindrical threaded pin	Tool rotational speed, Plunge depth, Welding speed	• Thermal imaging, tensile test and flexural test has been conducted. • Joint strength increases with an increase in tool rotational speed.
Singh et al. [19]	High-density polyethylene and Polyamide (PA6) sheets	2344 H13 steel tool with cylindrical threaded pin	Pre-heating, Tool speed, Feed rate, Plunging time	• Tensile and flexural test has been conducted in MADZUAG-X machine. • Joint strength growths with a surge in Pre-heating temperature, Tool speed, and Plunging time.
Sharma et al. [23]	Polylactic acid (PLA) sheets	H13 steel with cylindrical, cylindrical threaded and conical pin	Tool rotational speed, Welding speed	• IR imaging with 320 × 240 pixel used for temperature analysis. • The weld strength improved with a rise in the tool rotational speed.
Rehman and Sheikh-Ahmad [20]	High-density polyethylene sheets	Stainless steel coarse socket set screw pin	Tool rotational speed, Welding speed, Pre-heat temperature	• Preheating method used. • Weld strength enhances with an increase in preheat temperature.

moplastics weld quality prediction in FSW. Goswami et al. [9] proposed FSW to join dissimilar Al6061 aluminium alloy over polycarbonate sheets [10] and however there was a longitudinal weld groove was noticed at higher tool revolving speed (1400 rpm), because of over-heating at the interface of joint. This brief survey on this friction assisted stirring processes on weld quality characteristics of thermoplastics materials have been summarized tabulated in table 1.

Conclusions

This brief survey on the friction stir welding of dissimilar thermoplastic indicates the feasibility of friction stirring processes for the joining of lightweight thermoplastics that is used in many engineering applications. In this review, the effect of a process parameter, tool shape, its tilting and axial load on weld joint strength and its bead profile has been summarized with tabular format for better clarity in understanding. The summarized conclusions are indicated below.

- The tensile strength of friction stir processed high density polyethylene improves at higher tool rotational speed (1600 rpm) with addition of graphite powder. However, the joint strength of high-density polyethylene can be further improved at lower rotational speed (630 rpm) and higher tilt angle (2 degree) with addition of $Fe\text{-}Fe_3O_4$.
- The Joint efficiency of thermoplastic polycarbonate as well as Nylon-6 weld can be significantly improved (above 10%), in similar butt configuration, at intermediate revolving speed (1800 rpm) and lower welding speed (20 mm/min).
- The uniformity in weld bead contour is noticed to be better for both higher tools turning speed (1300 rpm) and traverse speed (60 mm/min) for polycarbonate to AA6061 alloy using FSW.
- The taper and taper threaded pin geometry may be suitable for unlike thermoplastic polymers joining using FSW.
- The hardness of the weld stirred zone is relatively higher due to grain refinement.
- Mechanical interlocking plays a key role for the joining of dissimilar thermoplastic materials.
- The axial thrust force with tool stirring torque signals are useful for the process monitoring.

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None.

Conflict of Interest

The authors declare no conflict of interest that are relevant to the content of this article.

Credit Author Statement

Nisith Kumar Goswami: Conceptualization, Methodology, Writing - original draft preparation; Lalita Prasad Nayak: Investigations, Analysis, Writing - review and editing; Kamal Pal: Writing - review and editing, Supervision. All the authors read and approved the manuscript.

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