Friction Stir Welding of Polymers: An Overview

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Abstract Friction stir welding, a solid state joining process is an already proven technique for the welding of metals. Lately, it has been employed on polymers, which also have shown efficacious joining results. Due to recent consideration of this process on polymers, a limited body of literature on friction stir welding of polymers exists. This paper presents an overview of the state-of-the-art of the process on similar and dissimilar polymers. The process parameters which are significant for weld strength and various approaches to maximize it, such as external heat induction, tool modification, and material flow are central to this discussion. Finally, the conclusions drawn with future recommendations are reflected as well.

1 Introduction

Considering the light weight property of polymeric materials, their use has grown widely in various industries, mainly in electronics, automotive, aerospace, and packaging [1]. Due to the dissimilarity in materials and complexity of joining parts, the increased use of any material at the same time increases the importance of the joining process. Several joining techniques for similar and dissimilar polymeric materials are employed in many industries. The invention of modern welding processes such as friction welding, resistance, ultrasonic, laser, induction, and microwave welding has widely replaced conventional joining processes (adhesive and mechanical fastening) [2]. However, these modern processes require high initial investment which limits their scope of application. Better mechanical properties

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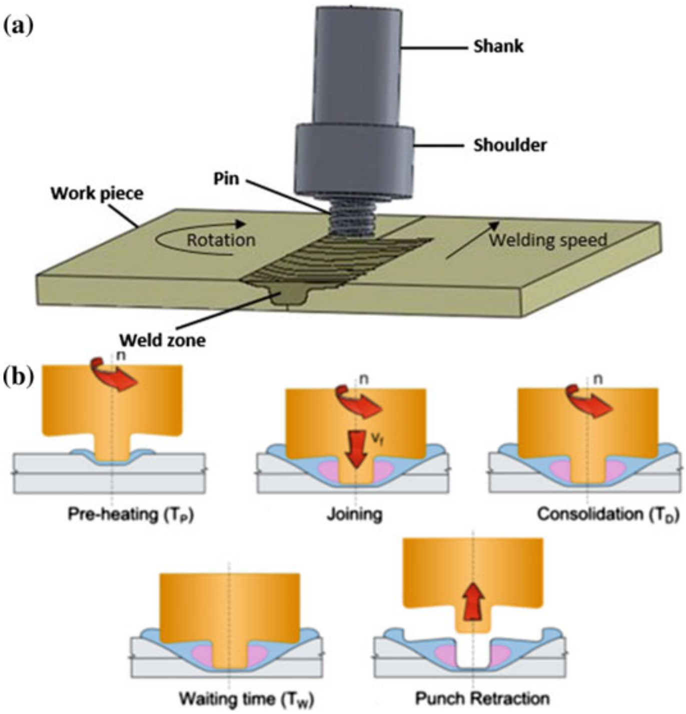

Fig. 1 A schematic representation of **a** FSW and **b** FSSpW process [1]

with low investment cost have been obtained by friction stir welding (FSW) and friction stir spot welding (FSSpW). FSSpW is the variant of FSW by the elimination of transverse part and involves plunging and retraction at one spot. A schematic view of both processes is shown in Fig. 1. These friction based processes have many other advantages such as solid state welding, flexibility, and insignificant heat-affected zone (HAZ) in polymers [3].

Among three kinds of polymeric materials; thermoplastics, thermosets, and elastomers, only thermoplastics are the weldable polymers. It is due to their ability to be reshaped after heating below their degradation temperature. Examples of such polymeric materials include Polyvinyl chloride (PVC), Polystyrene (PS), Acrylonitrile Butadiene Styrene (ABS), Polymethyl methacrylate (PMMA), low-density and high-density polyethylene (PE). Others are Polypropylene (PP), Poly tetra fluoro ethylene (PTFE), nylon-6 (PA 6), and polycarbonate (PC) [4]. Due to different rheological properties of theses polymers particularly melt viscosity, their flow behavior is also different. This difference leads to the diversity of process parameters as well as pin profile in FSW process.

The joining mechanism in welding of polymers is based on molecular diffusion and chain entanglement which starts at the molten stage of the polymer. After cooling and solidification of the weld, residual stresses due to squeeze flow will remain in the weld [5]. Grewell [5] has mentioned that a high squeeze flow rate will lead to a certain molecular alignment direction which ultimately influences the weld quality and may result in a weak weld. Moreover, the degree of welding also depends on the kind of polymer used, its properties, and the joining parameters.

The present review focuses on using the FSW and FSSpW to join similar and dissimilar polymers. Firstly, it describes the problems and challenges surmounted to friction stir weld the polymeric materials. This is followed by a detailed description of progress so far achieved on the FSW of polymers. Finally, conclusions are made with a particular view on future research challenges and directions.

2 Friction Stir Weldability of Polymers

FSW of polymers is critical due to different physical and rheological differences present in each polymer. The achievement of optimum process parameters becomes more challenging when it comes to weld polymers which have low melt viscosity such as nylon-6. Rotational speed is the major process parameter in FSW process which varies for each kind of material depending on their physical properties [6]. A higher rotational speed results in the degradation of the polymer, whereas lower rotational rate gives poor mixing thus producing voids in stir zone. Therefore, the need to investigate the optimum parameters for each polymer is vital.

On the other hand, squeeze-out of plasticized or semi-molten material is also an important consideration to achieve maximum weld strength as it may result in flash formation and eventually a poor surface finish [7]. An example of over plasticized material's squeeze out as observed in PC is shown in Fig. 2. In addition to that, an excessive flow-out of the material may result in tunnel defect which will ultimately reduce the weld quality. The uniform mixing of material during the stirring process has a direct relationship with weld quality [8]. On the other hand, uniformity in material flow or mixing depends on the geometry of pin profile [9]. Therefore, optimum pin profile for uniform mixing should also be evaluated to widen the scope of FSW on polymers.

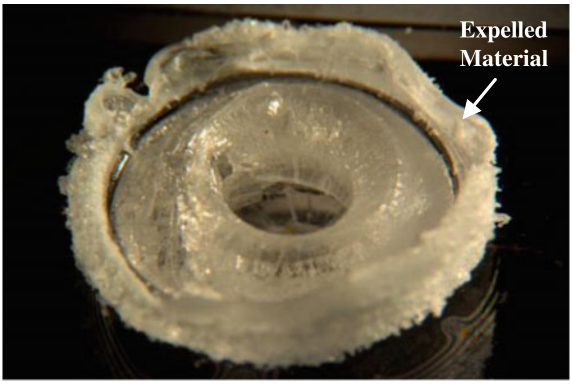

Fig. 2 Expulsion of plasticized material during FSW of PC [10]

3 The Research Progress in Friction Stir Welding of Polymers

FSW and FSSpW of polymer have continued to develop rapidly in recent years with advances made in tool design, external heat introduction, and different submerging conditions. Moreover, material flow during welding has also been studied using marker insert technique. This review presents a comprehensive review of all investigations made to maximize the weld strength. Table 1 is the sum of the findings on FSW and FSSpW which was performed on different polymers.

3.1 Optimum Welding Parameters for the FSW of Polymers

The FSW require very few process parameters (rotational speed, welding speed, tool dimension, and plunge depth) [24] and each parameter has vital roles in heat generation and stirring. The optimization of parameters is significant to produce an acceptable joint strength. Due to different rheological and physical differences among polymers, they were welded at diverse FSW parameters. Besides, it was discovered that workpiece thickness profoundly influences the welding parameters. Also, researchers have reported different joining parameters for various levels of thickness of the same material. For instance, Azarsa et al. [21] welded 10 mm thick high-density polyethylene (HDPE) at 1400 RPM rotational speed and 25 mm min^{-1} welding speed with the joining strength almost equal to the base material. Bozkurt [6] welded thin (4 mm) HDPE sheet at higher rotational and welding speed which is 3000 RPM and 115 mm min^{-1} respectively. Although there is a significant difference in joining parameters of both studies, the joint strength in thin sheets is only 10% lower when compared to thick sheets. The decrease in strength could be due to higher rotational rate which generated high temperature i.e., 165 °C which is higher than HDPE melting point (132 °C).

The similar difference of process parameters (rotational and welding speed) has been found during the FSW of nylon-6; however, the difference of joint strength is negligible at different thicknesses of the workpiece. Inaniwa et al. [11] joined the 5 mm thick nylon-6 at 440 RPM rotational speed and 40 mm min^{-1} welding speed with a tool shoulder-workpiece gap of 0.1 mm. Panneerselvam et al. [7] welded 10 mm thick nylon-6 sheet at 1000 RPM rotational speed and 10 mm min^{-1} welding speed with a tool shoulder-workpiec gap of 0.5 mm. In a recent study, Zafar et al. [25] further increased the nylon-6 sheet thickness to 16 mm and successfully welded without any gap (zero plunge depth) between tool shoulder and workpiece. However, in the study by Zafar et al. [25] the rotational speed and welding speed was reduced to lower levels, i.e. 300 RPM and 25 mm min^{-1} respectively. Overall, the joint strength at any thickness remained between 30 and 40% of the base material. The difference in the welding speed in all three studies on nylon-6 is minimal. The rotational speed difference may be attributed to the tool

Table 1 States of the art in polymer friction stir welding

Author (s)	Base material	Plate thickness (mm)	Tool/pin profile	UTS (MPa)	Joint efficiency (%)
Inaniwa et al. [11]	Nylon-6	5	Threaded	67.1	35
	High-density polyethylene (HDPE)	5	Threaded	31.9	70
	Polyvinyl Chloride (PVC)	5	Threaded	66.5	45
Panneerselvam et al. [7]	Nylon-6	10	Threaded	34.8	40
Zafar et al. [12]	Nylon-6	16	Threaded	27.22	32
Sadeghian et al. [13]	Acrylonitrile butadiene styrene (ABS)	8	Cylindrical	41.42	99.1
			Conical	39.30	94
Bagheri et al. [14]	ABS	5	Threaded	32.62	88.76
Pirizadeh et al. [15]	ABS	5	Double shoulder tool with convex pin	20.7	60.6
			Double shoulder tool with simple pin	15.58	45.6
Mendes et al. [16]	ABS	6	Stationary shoulder with conical threaded pin	29.48	67
Oliveira et al. [17]	Polymethyl methacrylate (PMMA)	3	Refill friction stir spot welding tool	9.5	11.87
Ahmadi et al. [18]	PP	4	Simple cylindrical conical	5.7	–
			Threaded conical	3.84	–
Kiss et al. [19]	PP	15	Traditional milling tool	11.5	50
Bozkurt [6]	HDPE	4	–	19.4	86.2
Gao et al. [20]	HDPE	4	Threaded cylindrical	12.3	–
Azarsa et al. [21]	HDPE	10	Threaded	33.76	95.69
Arici et al. [22]	Medium-density polyethylene (MDPE)	5	Cylindrical	20	100
Aydin [23]	Ultra-high molecular weight polyethylene (UHMW-PE)	4	Threaded	28.5	89

shoulder-workpiece gap because a higher difference requires a higher rotational speed to generate heat. It was observed that when the gap between tool shoulder and workpiece is helpful to generate low heat at the workpiece surface, it also promoted flash formation. This is the reason that Zafar et al. [25] concluded in their study that the insignificant flash formation at the workpiece surface as observed in Fig. 3, represents the cross-sections of best-welded joints.

Another polymer of nylon family, nylon-66, has been friction stir spot welded (FSSpW) by Husain et al. [26] and it showed an increase in the welding strength with the increase of rotational speed at a limit of 1570 RPM. The further increase in rotational speed (higher than 1570 RPM) resulted in the decrease of strength due to higher heat generation. However, a fall in joint strength was observed with the increase of welding speed. The maximum relative joint strength was pegged at 55% in comparison with the base material.

While achieving the operative conditions in FSSpW of thermoplastic materials, various approaches have been developed to determine the parameters relation with joint strength. For example, Paoletti et al. [1, 10, 27] developed a prototypal setup to observe the effect of plunging force, torque, and tool temperature during the FSSpW of 3 mm thick Polycarbonate (PC). The results were used to develop an Artificial Neural Network to predict the maximum values of parameters as well as the shear strength of the joint. According to experimental results, the shear strength of welded joint is primarily influenced by the plunge rate, the rotational speed, and the waiting time (post-weld cooling time). The maximum lap shear strength was obtained at lower values of tool rotational speed, plunge rate and at high values of pre-heating, as well as dwell and waiting times.

As far as dissimilar FSW of polymers is a concern, it is not well investigated compared to metals [28]. In a reported work, Dashatan et al. [29] showed the feasibility of dissimilar polymer joining by FSSpW of PMMA and ABS. In their study, it was found that welding parameters, particularly rotational speed and plunge rate, have a significant effect on the joint strength. Lap shear strength results indicated that 800 RPM is an optimum rotational speed as at below and above this value; a decrease in strength was observed. Low rotational speed caused lack of heat generation, while high rotational speed led to extra heat, which squeezed-out the over-plasticized material. Tool plunge rate had an inverse relation with the

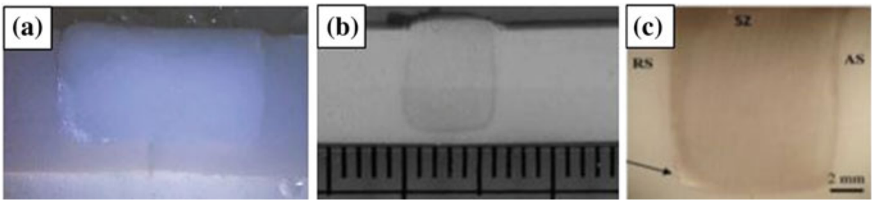

Fig. 3 Cross sections of friction stir welded nylon-6 specimens **a** 5 mm thick [11] **b** 10 mm thick [7] **c** 16 mm thick [25]

strength of the weld because an increase in the tool plunge rate decreased the weld strength.

A similar role of welding parameters was reported by Eslami et al. [30] in their attempt to join the PP with PE. They friction stir welded the workpieces using a novel stationary shoulder tool. Results showed maximum tensile strength at 2500 RPM rotational speed and 100 mm min^{-1} welding speed. However, the samples welded under same welding parameters did not show a good reproducibility as had been observed previously in metal welding. This feasibility study of PP-PE, and PMMA-ABS joining by Dashatan et al. [29] however indicates the practicability of dissimilar joining in polymers. Further investigations on other dissimilar polymers joining should be conducted due to their wide engineering applications.

The plunge depth in FSW of polymer is crucial because a higher depth can exaggerate the heat at workpiece surface due to the thermal insulator nature of polymer. Bilici and Yukler [31] have mentioned the plunge depth effect in their study on HDPE using FSSpW. As depicted in Fig. 4, the joint strength increases to a certain level of plunge depth. The further increase in plunge depth resulted in the squeeze out of polymer which ultimately lowered its strength value. Furthermore, they observed two fracture modes in lap shear tests; cross nugget failure and pull nugget failure. The welded joint with higher strength fractured with pull nugget morphology was observed as well.

In conclusion, among all process parameters, rotational speed had a significant effect on joint strength. Bozkurt [6] mentioned 73.85% contribution of rotational speed to the overall welding parameters. As can be seen in Fig. 5, the least contribution was made by a tilt angle. However, no general trend can depict the relationship between welding and rotational speed. Figure 6 represents an optimum rotational speed and welding speed for different polymers recommended by researchers. Overall, it is clear that polyethylene is welded at a higher rotational and welding speed. Whereas nylon-6, due to its low melt viscosity, requires a lower rotational and welding speed.

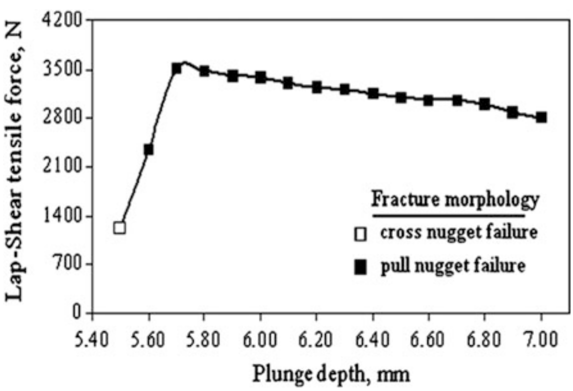

Fig. 4 The influence of tool plunge depth on lap-shear tensile strength [31]

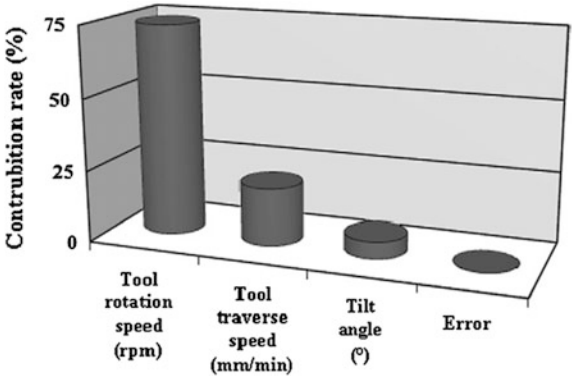

Fig. 5 Welding parameters' contribution rate [6]

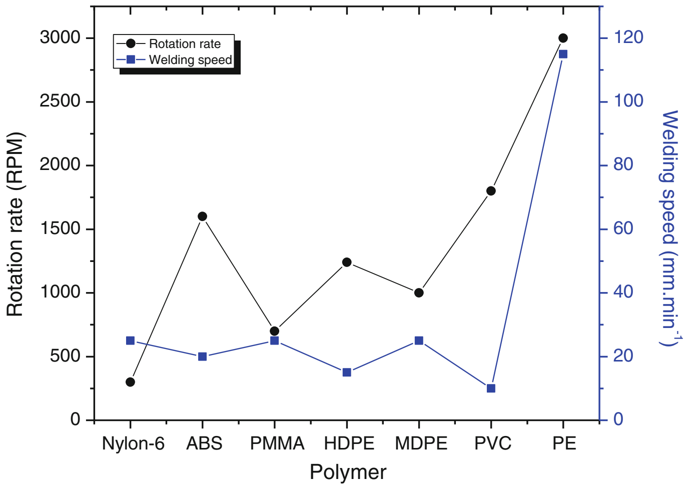

Fig. 6 Summary of optimum joining parameters for different polymers

3.2 Role of Tool Design on FSW of Polymers

In FSW, pin and shoulder geometry of the tool profoundly affect the weld quality [32]. Considering the importance of tool geometry, wide research on tool design has also been performed. Bilici et al. [33] studied the effect of six different commonly used pins on PP sheets in the FSSpW process. The types of pins studied included; straight cylindrical, tapered cylindrical, threaded cylindrical, square, triangular, and hexagonal pins as shown in Fig. 7. Results showed that the threaded pin with 0.8 mm pitch length has the highest tensile strength. Moreover, it was also observed

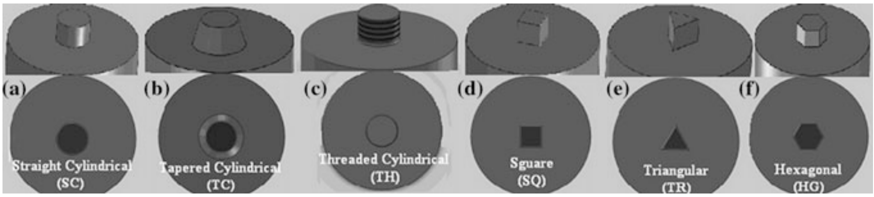

Fig. 7 Different pin profiles of tool for FSW [33]

that the pitch length of a pin type has a reasonable effect on the welding strength and it decreased with the decrease of pitch length.

Similarly, Ahmadi et al. [18] also studied the effect of pin profile on carbon fiber reinforced polypropylene composite in lap-joint configuration. They used four different pin profiles; threaded cylindrical, threaded tapered, straight cylindrical and straight tapered. Experiments conducted at fixed optimum parameters showed best tensile results for tapered threaded pin among the four pin profiles. They believed that it was due to the wider contact surface of the tapered pin with the specimen which resulted in high friction. On the other hand, the threads on pins caused a large amount of turbulence on the weld seam, which resulted in the better mixing of molten material and consequently, a better quality of the weld.

Besides pin profile, the effect of shoulder profile has been investigated on ABS by Sadeghian et al. [13]. They used a specially designed concave shoulder with straight cylindrical and conical pins. This particular design of shoulder was made to restrict the generated heat of friction within the weld area. A stainless steel blade was also placed on the upper surface of the ABS sheets to prevent the top of the weld from undercutting thus producing a good surface finish. The tensile strength of specimens showed effective results as the highest weld efficiency was pegged at 101 and 99% in the conical and the cylindrical pinned tools, respectively.

The novel designs of tools have also been employed. In a preliminary study, Oliveira et al. [17] joined thin PMMA sheets using refill friction stir spot welding. This process is efficient in a way that a key-hole will be filled by a non-consumable FSW tool. The schematic of the tool is shown in Fig. 8a. The details of the tool design and its working principle have been described in the study conducted by Goushegir et al. [34]. The maximum achieved joint lap-shear strength was about 9.5 MPa. Comparing with other joining techniques including microwave welding, thermal bonding, and ultrasonic welding, they found that friction spot welding gave a higher strength in a short joining time. The graphical representation is given in Fig. 8b. In another study, a novel robotic platform was developed by Mendes et al. [35] to increase the flexibility of the process. The platform consisted of three major groups of hardware; a robotic manipulator, an FSW tool, and support for the FSW tool. The setup as a preliminary studied on ABS showed comparable joint strength.

Having reviewed the literature, it is apparent that the pin profile plays a decisive role in determining the strength of the joint. The threaded pin, due to its ability to

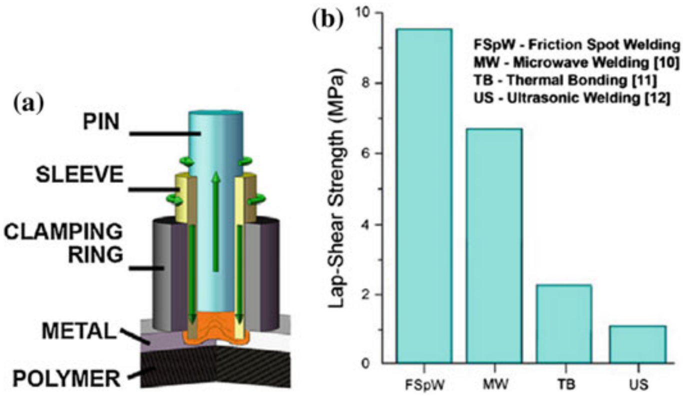

Fig. 8 **a** Schematic illustration of the refill friction stir spot welding tool. **b** Lap-shear strength comparison of FSSpW with other joining techniques [34]

adequately mix the plasticized material has shown good welding results. Moreover, a high surface area of threaded pin generates a higher frictional heat which is an essential pre-condition to produce a weld.

3.3 Effects of External Heat Induction

Due to thermal insulator nature of polymers, it is always difficult to conduct the shoulder generated heat to the base of workpiece. It may cause a heterogeneous mixing near the base, especially in thick sheets. This challenge was addressed by adopting different approaches. For instance, Aydin [23] pre-heated the ultra-high molecular weight polyethylene (UHMW-PE) sheets before employing the FSW. Pre-heating at 50 and 80 °C from the bottom of sheet was performed in the furnace. Comparing the tensile values of pre-heated specimens with non-heated specimens, the research found that the specimens heated at 50 °C temperature achieved a 17% higher strength. On the contrary, the strength of non-heated specimen was 72% of the parent material's strength. Although pre-heating showed good joining results, an additional heating step not only affects the simplicity of the process but also increases the process time.

The in situ heating during the FSW process could be a good approach to maintaining the process short joining time. Bagheri et al. [14] employed a heated shoe called 'Hot shoe' to improve the welding strength as well as to eliminate the defects in ABS joints. Hot shoe made from steel is an externally heated stationary shoulder which moves linearly along the tool. This hot shoe not only heats the specimen but also keep the plasticized material within the weld zone. Efficient results were obtained at higher rotational speeds, high shoe temperature, and lower welding speed. Lower welding speeds gave sufficient time for mixing and hence good welding strength was achieved. The highest tensile strength was almost 89% of the base material strength. In another study, Mostafapour and Asad [36] also used hot shoe to weld nylon-6. Results showed good welding results as tensile strength was almost equal to that of the base material.

Another approach to generating in situ pre-heat is given by Vijendra and Sharma [37]. However, in this technique, only the tool is heated through induction heating process, and constant temperature is maintained throughout the process. For this purpose, an induction coil encircling the tool was used and supplied with alternating current. This investigation showed remarkable results in which joint strength near to the strength of the base material was achieved at a tool-pin temperature of 45 °C, and a rotational speed of 2000 RPM. This approach of tool induction heating has some advantages over other heating methods. For instance, the shoe heating technique may not be used for curvilinear welds for the reason that pre-heating of tool might not perform longer welds because of dissipation in tool temperature, and external heating of tool will probably lead to erratic heating of the base material.

3.4 Submerged FSW of Polymers

Various researches into the FSW of metals in submerged condition have been conducted, and the results have been promising. [38]. Similar research is also required on polymers. However, in literature, a limited body of knowledge exists. Gao et al. [20], employed FSW on HDPE sheets under water and air and compared their tensile strengths. Experiments were performed at optimum welding parameters using a threaded cylindrical pin. Tensile test results showed that the welding performed under water had a higher tensile value when compared with welding performed in air. The maximum strength value under water was 12.3 Mpa, whereas it reduced to 9.6 Mpa in air. All the fractures were observed in the heat affected zone (HAZ). They believed that in a submerged condition, the water not only controls the peak temperature but also affect the thermal cycle of the weak part, resulting in the increase of joint strength.

3.5 Microstructure Evolution

Welding parameters have a direct relationship with the microstructure of the material and hence the quality of the weld. During FSW, the workpiece undergoes intense heating which results in microstructural changes and different zones formation. In metals FSW, four different zones: the weld nugget (WN), thermo-mechanically affected zone (TMAZ), heat-affected zone (HAZ) and base material (BM) are observed [3]. However, in the case of polymers, HAZ is not always present. Moreover, the microstructure observed in the welded zone is different from metals. Kiss et al. [39] studied the morphology of weld seams of friction stir welded

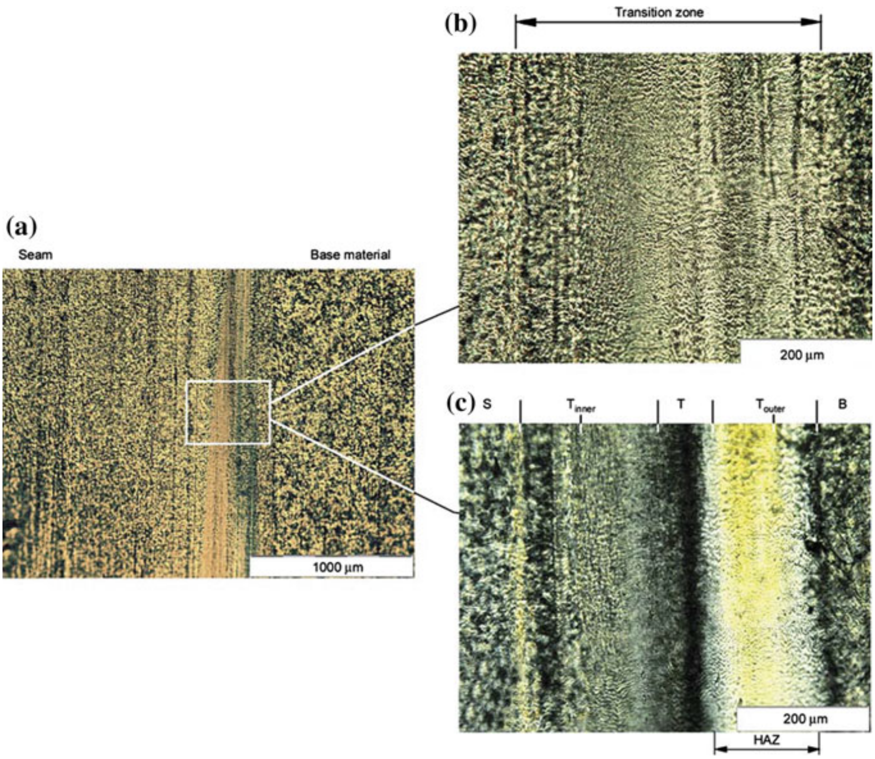

Fig. 9 **a** Spherulitic structure in the seam and base material. **b** and **c** Supermolecular structure in the border region [39]

PP sheets. As shown in Fig. 9, the results of optical microscope showed spherulitic structure at the center and base material. The structure at the center was similar to that of the base material. They believed that to achieve good weld quality; the welds should have less complexity in morphology with small seam width.

3.6 Elimination of Root Defect in FSW of Polymers

After the successful application of FSW on polymers, attempts have been made to eliminate the associated defects to improve the welding strength. Root defect which occurs due to incomplete penetration of tool has a direct influence on the tensile strength of weld [40]. In most tensile failures, it has been found that fractures were initiated by root defects [41]. Various approaches such as double shoulder scheme and double passes of the tool have been used to eliminate this defect. Arici et al. [22] employed the double passes of the tool on medium density polyethylene (MDPE) sheets. In their process, welding was performed in two steps. In the first

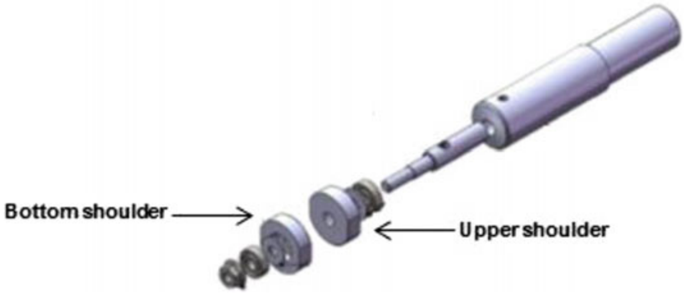

Fig. 10 A novel design double shoulder tool [15]

step, half thickness of specimen was friction stir welded, while the remaining half was welded in the second step by turning back the specimen in the fixture. Results showed the root defect free specimen with an increased tensile value.

In another study, Pirizadeh et al. [15] used a newly designed tool which consisted of two shoulders and was capable of contacting upper and lower surface of the workpiece during the process. The tool is shown in Fig. 10. This tool was designed to eliminate the root defect in samples. As a working principle, shoulders were kept stationary during the process by placing the ball bearings and thus there was only pin rotation. The experiments were conducted on 5 mm thick ABS sheets. After welding, no root defect or back slit was observed. Tensile results showed that the highest tensile value was almost 60% of the base material.

3.7 Effects of Crystallinity on the Properties of Polymer

The crystallinity of polymer indicates the extent of structural order. A fully crystalline material has atoms or molecules in an ordered and periodic manner [42]. The degree of crystallinity has a significant influence on the properties of materials. It includes tensile strength, stiffness, yield point, hardness, and impact strength. Increase in crystallinity has shown an increase in tensile strength and hardness with the loss of impact strength [43–45]. The degree of crystallinity is usually measured regarding percent crystallinity by differential scanning calorimetry. Percent crystallinity is an overall crystalline content in comparison to its amorphous component [46]. On the other hand, differential scanning calorimetry (DSC) is a method which measures exothermic or endothermic heat flow of a material as a function of time or temperature. Polymer crystallinity can be found with DSC by measuring the heat of polymer fusion. This heat gives the percent crystallinity by rationing against the heat of fusion for a 100% or fully crystalline specimen of the same material [47].

Gao et al. [20] measured percent crystallinity of friction stir welded HDPE samples at different conditions such as base material (BM), HAZ, thermo-mechanical affected zone (TMAZ), and weld nugget (WN). These regions are

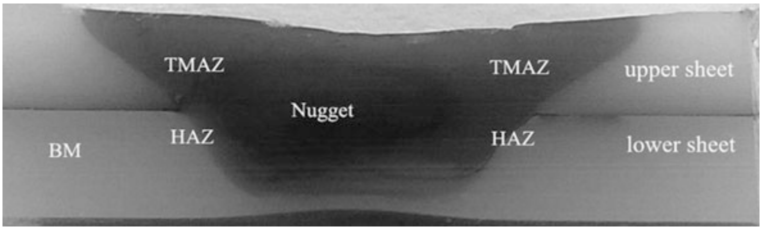

Fig. 11 Different regions formed during FSW [20]

shown in Fig. 11. DSC curves were used to determine percent crystallinity using the formula given below;

$$\mathbf{Wc} = \frac{\mathbf{\Delta Hm}}{\mathbf{\Delta H^{\circ}m}} \times 100\%$$

Results showed a decrease in crystallinity while approaching from BM to WN. They believed that FSW was a fast welding process which resulted in a decrease of crystallinity due to rapid cooling of the weld zone. It is important to mention here that rapid cooling causes the loss of crystallinity in the material [48].

Another study was performed on friction stir welded PP specimens by Kiss et al. [19] using a Perkin-Elmer differential scanning calorimeter at a heating rate of 10 K min^{-1}. The results showed almost the same trend as reported by Gao et al. [20]. Weld Nugget (WN) was found to have the lowest crystallinity as compared to other regions. They believed that it was due to a larger tool size compared to the WN which rapidly absorbed the heat from WN. As a result, fast cooling caused the lower crystallinity in WN. The region at a distance from the tool had more time for cooling which made it a comparatively high crystalline.

3.8 Material Flow During FSW Process

The understanding of the material flow is important in preventing blowholes and other defects which may form during the stirring process [49]. These defects also affect post weld microstructure and mechanical properties. Therefore, the study of material flow in both sides; advancing side (AS) and retreating side (RS) of the tool is critical. Limited literature exists on the material flow during FSW of polymers. Simoes et al. [50] studied material flow on PMMA sheets using two different tools. Tool 1 had a small diameter of shoulder with a conical profile, whereas tool 2 had a large diameter with a conical profile near the center. Comparing their results with Arbegast [51] flow model study on metal, they believed that the material flow in polymers is different from that of metals. Also, they reported that the interface of pin plunged zone and the base material remained straight which showed no material

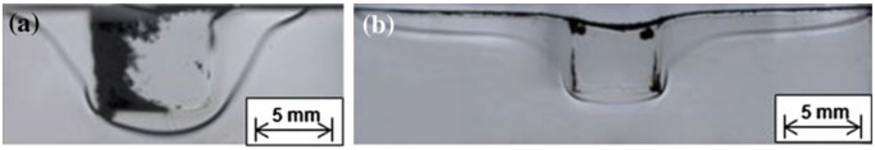

Fig. 12 Backlight images of Friction stir welded PMMA (transparent in nature) **a** Tool 1 **b** Tool 2 [50]

flow from stir zone to the base material. The images of both specimens are shown in Fig. 12.

A similar observation of material flow was noted during FSW of nylon-6 by Zafar et al. [52]. Also, during visual analysis made at different sections of welded specimens, an overall uniform material mixing was observed. The vertical, as well as the horizontal displacement in which material moved from AS to RS and vice versa, show the successful feasibility of the process on polymers.

4 Conclusions

Friction stir welding, after its successful application on metals, has been successfully utilized for polymers. A variety of thermoplastic polymers has been friction stir welded and investigated regarding their micro-mechanical and thermal properties. We found that depending on their physical and rheological properties, the welding parameters differ from polymer to polymer. Polymers with high melting temperature and viscosity, require higher rotational speed and low welding speed to achieve sufficient heat and eventually good weld strength. Moreover, to enhance the welding strength, hot-shoe utilization or an in situ induction heating of the tool has shown good results. In the evaluation of appropriate pin profile, we saw that it varies from polymer to polymer. For example, the conical pin is reported as best profile for acrylonitrile butadiene styrene and high-density polyethylene, whereas the threaded cylindrical pin profile is considered most suitable for polypropylene friction stir welding. Furthermore, we found that different pin profiles also led to different material flow. However, a uniform material flow which is a bit like flow in metals, have also been observed.

5 Recommendations

The joining of polymers using FSW is still under development and therefore has not yet been fully employed in the industry. The results showed that it is a potential welding process; however, some further modifications and investigations are required to make it fully utilized. There should be a comprehensive study on the plunge depth relation with joint strength. More work is needed to understand the welding parameters-microstructure relation. Also, there is a need to understand the bonding mechanism of dissimilar polymers so that the scope of the process could be extended to other polymers. Furthermore, the application of the process for different joint specifications while maintaining the process simplicity and flexibility could be a significant achievement to implement the process in the industry.

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