Friction Stir Welding of Polymers

Subjects: Polymer Science

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Friction Stir Welding (FSW) is one of the welding methods within the category of friction welding, as it uses the friction between the base material and the tool to generate the heat necessary to soften the material of the joint. The FSW process was developed, demonstrated and patented by “The Welding Institute (TWI)” in England for the first time by Thomas et al.. The principle of the conventional process is illustrated in, as well as its main variables.

Keywords: friction stir welding (FSW) ; joint efficiency ; stationary shoulder ; external heating ; double-side passage ; polymeric materials

1. Introduction

Low density, good moldability, excellent resistance to corrosion and low production costs are some of the characteristics of polymeric materials that have led to the substitution of many materials by polymers in many sectors of industry, especially in the automobile, naval and aerospace sectors [1]. In the case of polymeric materials, the main joining methods are divided into mechanical fastening, adhesive bonding, and welding. Welding currently involves the melting of a portion of material that, after cooling and solidifying, gives rise to the welded joint [2]. Welding processes can be divided into three different categories, depending on the melting process associated, which are thermal welding, friction welding and electromagnetic welding [2][3].

Many welding technologies have been tested in welding of polymers in recent years, of which the most notable are: laser welding (LW) [4][5], ultrasonic welding (USW). Friction stir spot welding (FSSW) and friction stir refill spot welding (FSpW) are variations of FSW where there is no linear movement of the tool, which only allows spot welding, resulting in the stress concentration and does not guarantee a watertight weld. In addition, all these processes produce welds with relatively low joint efficiency. Pereira et al [6] refer to a maximum joint efficiency of 50% for the Nd: YAG Laser welding of double-bead lap joints in PA.

Friction Stir Welding (FSW) is one of the welding methods within the category of friction welding, as it uses the friction between the base material and the tool to generate the heat necessary to soften the material of the joint [7]. These main variables are the rotational speed, welding speed (or traverse speed), tilt angle (or attack angle), axial force and plunge depth (or penetration depth). The conventional tool consists of a shoulder and a pin that rotate together, generating heat that is responsible for heating and softening the material to be welded. Butt and lap joint configurations are the most common in FSW, although other configurations can be used [1].

This welding method was developed to overcome the difficulties of traditional welding techniques when applied to lightweight alloys and was initially used to weld aluminium alloys. After proving its potential, FSW was also applied to other metals and their alloys, such as magnesium, copper, titanium and steel [1][8], and it was first demonstrated on polymers in 1997 [2].

[9] mentioned that the melting temperature is never reached during FSW of 5 mm thick plates of high density polyethylene (HDPE), polyamide 6 (PA6) and polyvinyl chloride (PVC) in butt joint configuration. Polymeric materials have a temperature range in which the change of phase occurs, because they are composed by molecular chains with different lengths and molecular weights and therefore, with different melting temperatures. Similar conclusions were presented by Bozkurt [10] after measuring temperatures between 120 and 165 °C while welding 4 mm thick HDPE plates in the butt joint configuration. [11], during the FSW of 3 mm thick high molecular weight polyethylene (HMW-PE) plates in butt joint configuration, also measured temperatures above the welding temperature of the polymer which according to him, reinforces Stand’s theory [7].

FSW and other welding processes cannot be applied to all types of polymers because thermosetting polymers show irreversible transformations when exposed to high temperatures, due to the change in their molecular structure, even below the melting temperature. On the other hand, thermoplastic polymers soften when exposed to a temperature increase, without a degradation of their molecular structures. They are also known as recyclable polymers, due to the possibility of being moulded more than once [1][12]. This technique has successfully joined: acrylonitrile butadiene styrene (ABS) [13][14][15][16], polyamide 6 and 66

New techniques have been developed in recent years to resolve the problems identified concerning the conventional FSW of polymers. For example, the root defect corresponds to an area at the bottom of the joint that is not welded, because the heating of that zone was inadequate [7]. Therefore, the lack of welding at the root of the joint results in a decrease in the tensile and flexural strengths of the weld [17]. To solve this problem of the root defect, which frequently occurs in conventional welding, Arici and Sinmaz [17] performed welding on both sides of the polymers to be joined (double-side passage), thus completely eliminating this defect.

Another innovation related to the FSW of polymeric materials was the introduction of stationary shoulders. According to Strand [7], a tool with a rotating shoulder is not able to retain the polymeric material inside the weld seam as happens in the FSW of metals. With the introduction of non-rotating shoulders, it was possible to reduce the amount of material pushed out of the weld volume and to improve the surface finish of the weld significantly. The use of stationary shoulder tools is also beneficial to the FSW process for polymeric materials, specially to solve the peeling effect and the rough surface finish of the conventional process [1].

Because FSW operates at lower temperatures than conventional welding methods, heat conduction plays a very important role in the performance of this process. Since polymers have low thermal conductivity, mainly due to their molecular structure, heat conduction in polymeric materials is less efficient, which makes it difficult to achieve strong FSW joints [18]. To overcome this difficulty Aydin [19] preheated the polymer before welding which allowed them to remove any cavities and improve the joint efficiency.

[20] reported that the use of a conventional tool provides welds in polymers with inadequate morphology and mechanical resistance and patented a tool with a stationary shoulder and heated by electrical resistances. [15] developed a long stationary shoulder tool with a conical threaded pin in the centre of it, which can be used with or without electrical heating, and mounted on a robot [21]. Because the pin is in the centre of the shoe, the cooling stage may be controlled, as with other versions of hot shoe tools, but with better preheating of the material. The shoulder is made of aluminium, to ensure good thermal conductivity, and the cylindrical holes serve to mount electrical resistances.

Recently, Eslami et al. [11] developed a very simple FSW tool with a stationary shoulder made of Teflon, without external heating, but where part of the heat is generated by the friction between a copper sleeve and the pin, and not just between the pin and the polymer. A scheme of the tool is shown in**Figure 1**b.

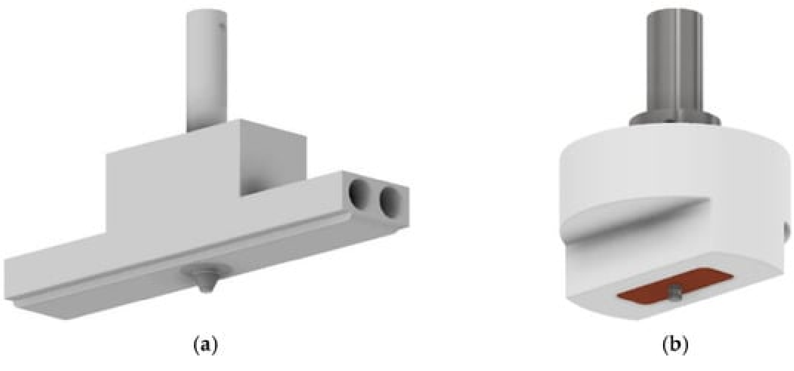

Figure 1. (**a**) FSW tool with stationary shoulder, with external heating (adapted from [15]) and (**b**) FSW tool with stationary shoulder, without external heating (adapted from [11]).

FSW of polymeric materials continues to be studied and is responsible for a very significant number of published papers, including some reviews of relevant interest [22][23][24][25][26]. Therefore, the aim of this study is to analyse, compare and summarize the effects of conventional and alternative FSW techniques and tools, as well as the main process parameters, on the quality of welds in thermoplastic polymers based on the literature published. The bibliographic search that supports the current study focused mainly on papers that show the efficiency of the joints, or that provide enough information for their estimation. Data were divided into the following categories taking in consideration the tool or procedure used: conventional tool, conventional heated tool, tool with stationary shoulder, tool with heated stationary shoulder, double-side pass, and preheated polymer.

2. Graphical Presentation of Data

As mentioned above, the quality of FSW welds, and consequently their mechanical strength, depends on many parameters, so the analysis of their influence is a complex task. Therefore, it was decided to use in the current study the ratio between the speed of rotation (w) and feed (v) of the tool, because they are two of the main parameters of the FSW process. Furthermore, the increase in the rotational speed and the decrease in the welding speed increase the frictional heat input in the weld, which, as will be seen later, has a crucial influence on the quality of the welds.

On the other hand, joint efficiency is used in the current analysis to evaluate the strength of the welds, because it is a parameter available in many papers, or at least the strength of the welded joints is given, which allows the calculation of the joint efficiency. The joint efficiency is the ratio between the mechanical strength of the weld and the strength of the base polymer. Flexural strength, elongation at break, crystallinity and hardness were also evaluated in some studies, but with much less frequency. Although these results were not used to establish a direct comparison between studies, their influence was also considered in the current article.

The effect of the tool rotational speed to the welding speed ratio (w/v) on the joint efficiency of the welds of PE and PP is shown in **Figure 2** and **Figure 3**, respectively. In the current study, medium density polyethylene (MDPE), high-density polyethylene (HDPE), high molecular weight polyethylene (HMW-PE) and ultra-high molecular weight polyethylene (UHMW-PE) were included in a generic category called PE.

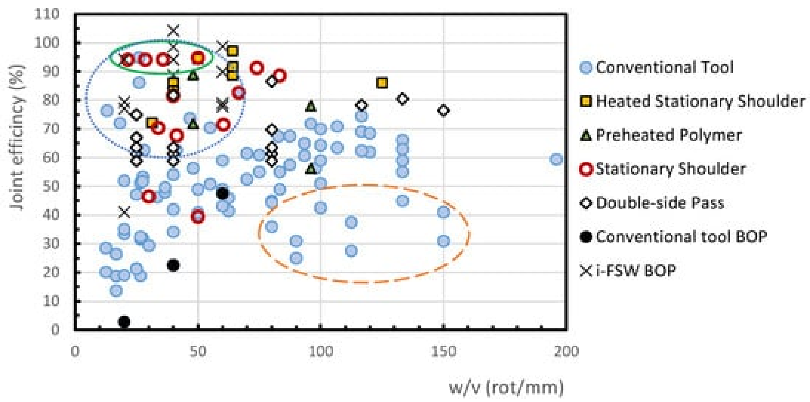

Figure 2. Effect of the *w/v* ratio on the joint efficiency of FSWs in PE.

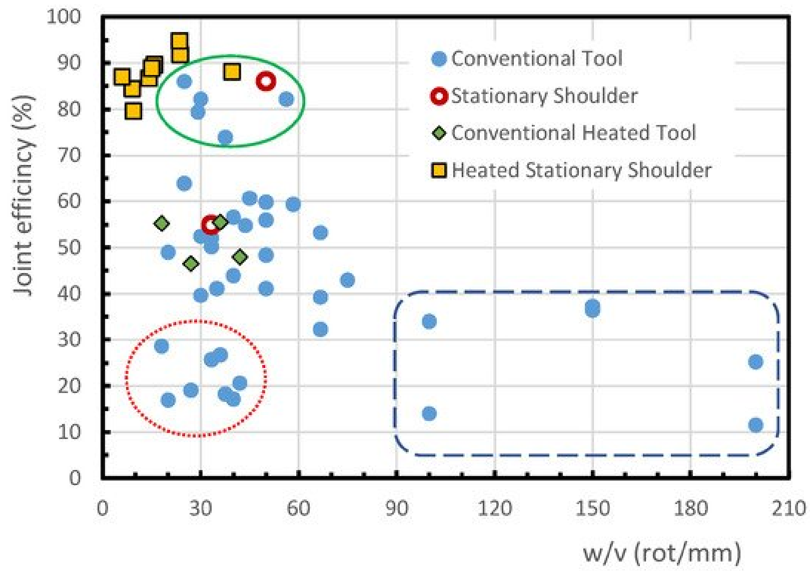

Figure 3. Effect of the *w/v* ratio on the joint efficiency of FSWs in PP.

Figure 2 and **Figure 3** include the results of joint efficiency of welds produced by FSW process using conventional tools with and without external heating, welds with stationary shoulder tool, with and without external heating, welds with preheating of the base polymer and welds with double welding passage. The conventional process is one that is carried out with a conventional tool, that is a tool composed by a shoulder and a pin rotating together, as mentioned above.

As the (w/v) ratio does not consider the heat input by external sources, such as when using tool with heated stationary shoulder or previously heated polymer, these figures also allow comparisons between FSW with conventional tool and the innovations brought to the welding process. These aspects will be analysed in detail in the following sections.

3. Data analysis

In order to understand the effect of the technological innovations on the FSW of polymeric materials, it is important to firstly understand the performance of the conventional process. For the welding of PE, most of the data related to the conventional FSW process, illustrated by filled dots in **Figure 2**, show that by increasing the w/v ratio the joint efficiency tends to rise. A maximum value of joint efficiency of about 75% is reached for a w/v ratio of about 120 rot/mm (rotations per millimetre). Exception to this trend are the points with high joint efficiency, which are inside the dotted circle, that belong to a study carried out by Bozkurt [10], and the points with low efficiency, located within a dashed oval, of an investigation done by Saeedy and Givi [27].

The application of conventional FSW for 6 mm thick MDPE in butt joint configuration was investigated by Saeedy and Givi [28]. These researchers observed that the rotational speed had a greater impact on elongation and the tilt angle on the tensile strength. They observed that the tensile strength and elongation were higher with a tilt angle of 1°, a rotational speed of 1600 rpm and a welding speed of 15 mm/min, which means an optimum value for the w/v ratio of about 133.3 rot/mm. According to these researchers, it was not possible to achieve better results due to the occurrence of root defects and due to the insufficient heat generated, which also contributed to the formation of heterogeneous structures.

FSW on MDPE of 8 mm thick plates in butt joint configuration was performed to test the influence of tilt angle, rotational speed and welding speed, by Saeedy and Givi [27]. The optimum parameters found were a tilt angle of 1°, a rotational speed of 1400 rpm and a welding speed of 12 mm/min, which means a w/v ratio of about 116.7 rot/mm and a maximum joint efficiency of 74.7%. Lower rotational speeds were not sufficient to soften the polymer and higher rotational speeds led to flash defects, according to the authors. According to them, lower welding speeds, and consequently higher heat inputs and longer cooling time led to the increase in the crystalline content and joint efficiency.

The application of FSW to several polymers was investigated by Inaniwa et al. Among them, 5 mm thick HDPE plates were welded by conventional FSW. In this case, a 0.1 mm gap was used between the shoulder and the plate surfaces, which means a negative plunge depth and a reduction in the compression on the softened material. In these conditions, no major defects were visible in the joint and a maximum joint efficiency of about 70% was obtained at a welding speed of 15 mm/min and a rotational speed of 1240 rpm, which corresponds to a w/v ratio of about 82.7 rot/mm.

They concluded that the rotational speed must be higher than 1000 rpm to assure a good mixing of the material, and less than 2200 rpm to avoid excessive temperature and, consequently, the degradation and burning of the polymer. According to the authors, this defect occurred due to insufficient heat generation and consequent deficient mixing of the material, which is related to low rotational speeds. They also observed that for welding speeds below 40 mm/min, material degradation occurred, due to the excessive temperature, and for welding speeds above 80 mm/min, the low operating temperature coupled to the deficient mixing of the material resulted in a reduction of the weld’s strength. The welding speed of 40 mm/min and the rotational speed of 2200 rpm, which corresponds to a w/v ratio of 55 rot/mm were responsible for the maximum joint efficiency for the new and conventional processes.

A joint efficiency of just 44% for a w/v ratio of 80 rot/mm was reached by Mishra et al. [1] for butt welds of 6 mm thick HDPE plates, because a tool rotational speed of only 800 rpm was used. They also reported that the rotation of the shoulder led to the peeling of the surface and consequently, tiny voids were formed on the surface. According to them, FSW of polymers should be performed with stationary shoulders, to avoid this phenomenon.

The optimization of the conventional FSW of 4 mm thick HDPE plates, in butt joint configuration, by testing different tilt angles, welding speeds and rotational speeds, was done by Bozkurt [10]. A maximum joint efficiency of 94.9% was achieved with 3000 rpm of tool rotational speed, 115 mm/min of welding speed (These points result from experimental sets performed with rotational speeds between 1300 rpm and 3000 rpm, welding speeds between 45 mm/min and 115 mm/min and tilt angles of 1°, 2° and 3°. No information about the axial force, penetration depth or pin geometry used is available in this study.

No article was found with a comparative study of the influence of the pin geometry on the strength of welds in PE, however, it was found that welds with high joint efficiency were obtained with threaded pins [19][29][30] or grooved pins [11].

It can therefore be concluded from the studies presented that the increase in the w/v ratio is beneficial for conventional FSW, because it increases the heat input and the plasticization of polymers, promoting the flow of material around the tool, thus reducing the root and internal defects in the welds. A research of one of the current authors [15] for welds in ABS plates confirms this trend. The use of a high w/v ratio does not guarantee that welds with a high efficiency will be produced, because the rotation of the shoulder causes the superficial degradation of the weld and excessive tool rotation speeds can burn the polymer. 3does not consider the influence of important parameters, such as tilt angle, axial force, tool plunge depth or tool pin geometry, that also affect the joint's quality and strength, and

A set of results may be observed within an oval dotted line with a joint efficiency of below 30% for w/v ratios below 50 rot/mm. Besides, **Figure 3** also shows some conventional FSW results, inside a dashed line, with a joint efficiency of below 40%, although the w/v ratio is equal to or greater than 100. The analysis of other factors, such as the tool tilt angle or the tool geometry, made it possible to highlight the influence of the tool pin geometry in the case of conventional FSWs. The effect of the tool pin geometry on the joint efficiency achieved by welds performed with different w/v ratios is shown in **Figure 4**.

[31], using tools with square or triangular prismatic pins, conical (also called taper) pins and cylindrical pins with or without thread for different w/v ratios. The welds made with the cylindrical threaded pin tool achieved the 4 highest joint efficiencies in **Figure 4**, between 79% and 86%. The authors also claimed that the pin geometry has an influence of about 50% on the final weld quality. With the tool of square pin, a maximum strength of about 75% of the base material strength was obtained for w/v= 40 rot/mm, as illustrated in **Figure 4**.

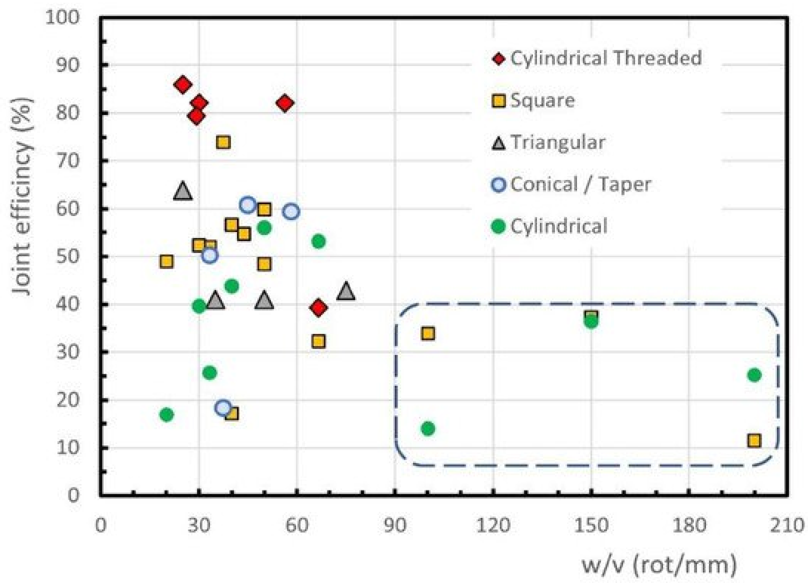

Figure 4. Effect of pin geometry on the joint efficiency for conventional FSW of PP plates.

Conventional FSW using square prismatic, cylindrical and conical pin geometries, all unthreaded, was performed by Sahu et al [32]. These welds could be broken easily by hand and therefore, the author decided to omit the values of the joint efficiency for this pin geometry. In general, the square pin performed welds with better tensile strength than the cylindrical pin, because it provides a better mixture of the molten material. For tools with square or cylindrical pin and very high tool rotation speeds (see dashed line of **Figure 5**) a reduction in weld efficiency is observed, due to the excess of heat generated.

The diameter of the tool shoulder also has a significant influence on the quality of the welds performed with conventional FSW tool. Increasing the diameter of the tool shoulder increases the heat generated in the process, which increases the distortion of the welded parts, as well as the material peeling rate of the weld surface, as mentioned by Sahu et al. [32].

Comparing **Figure 3** and **Figure 4**, there is an obvious difference in the trend for variation in joint efficiency with the w/v ratio between PE welds and PP welds. In fact, the joint efficiency increases with the w/v ratios of up to about 120 in most PE welds, in contrast to the PP welds, where the highest joint efficiencies are obtained for w/v ratios below 60 rot/mm. PP has lower thermal conductivity and specific heat than PE, so it should require a lower w/v ratio to provide adequate heat input to the polymer during welding. The presence of the weld root defect is influenced by the low thermal conductivity of the polymers and reduces the efficiency of the joint.

These researchers verified that conventional FSW, i.e., with a single passage of the tool on 3 mm thick medium density polyethylene (MDPE) plates, in butt joint configuration, led to the formation of the root defect. To evaluate the potential of a double-side passage of the tool, one in each side of the plate, to remove this defect, these authors double-side welded 5 mm thick MDPE plates with the same tool used before, with a pin length of 2.8 mm and 5 mm in diameter. Later, Arici and Selale [33] also performed double-side FSW on 5 mm thick MDPE plates with this same tool. In both cases, all the welds performed with a double passage did not present root defects and achieved better results in tensile and flexural strength tests.

The double-side passage of the tool was also studied by Saeedy and Givi [34], who welded 8 mm thick HDPE plates in butt joint configuration with single and double-side FSW and achieved similar results. While the single side passage achieved a maximum joint efficiency of 69%, the double-side passage of the tool achieved 81% for a w/v ratio of about 133 rot/mm, see **Figure 3**. They also observed that the crystallinity of the joint increased in the double-side welded samples, which resulted in higher impact strength. Although the authors do not mention any reason for this, the fact that the process is more efficient should lead to a lower number of welds being rejected, compensating for the increase in welding time.

For the comparison of the results of conventional FSW and those related to stationary shoulder FSW for PE and PP, see **Figure 3** and **Figure 4**, which show that most of the stationary shoulder joint efficiencies are above the conventional ones. This means that in general terms, the absence of rotation from the shoulder leads to higher joint efficiency. This behaviour is related to the better surface quality and/or the absence of internal defects in the welds produced with a stationary shoulder. These aspects depend on other factors too, such as the material to be welded or other welding parameters, as shown below.

The influence of the axial force, a parameter that is many times forgotten, was also considered in this study. This preheating effect allowed higher welding speeds to be used in the process and contributed to preventing the formation of the root defect due to the increase in the welding temperature. The high joint efficiencies achieved are related with this preheating effect and to the optimisation of the axial force. In this study, two experimental sets, resulting from non-ideal axial force, rotational speed, and welding speed, obtained joint efficiencies of under 50%, as illustrated in **Figure 3**.

The non-rotating square wooden shoulder with a support ring-wing made of bronze resulted in smooth surfaces. This technique produces welds with a good surface finish and free of defects. No voids or cracks were found in the microscopic analysis, which helps to explain the high joint efficiencies achieved. These authors state that the mechanical strength, hardness, and crystallinity of the welds decrease when the speed of rotation of the tool increases, but, in our opinion, not all these conclusions cannot be drawn from the results presented in the article.

The author’s aim was to identify the differences between a weld with a high tensile strength and another with a low one. Therefore, from this figure it should be concluded that the stationary shoulder allowed welds with high joint efficiency, but small difference in w/v ratio can ruin the results. The size of the spherulites of the two welds was approximately the same, which may be a consequence of similar cooling conditions. The authors also conclude that smaller weld seams with less complex morphologies result in better joint efficiencies of the FSW process.

By preheating the polymers, the amount of heat generated by friction required for the welding process is reduced. This technique may not be suitable for all applications, because the process of heating the polymer is slower than for metals. 3show that this technique makes it possible to achieve higher joint efficiencies for lower w/v ratio than with conventional FSW. This was understandable because if the heat required, generated by friction, is reduced, the rotational speed may be decreased, or the welding speed increased, to achieve the same heating temperature as the conventional process.

For the FSW of 4 mm thick ultra-high molecular density polyethylene (UHMW-PE) plates in butt joint configuration, Aydin [19] tried to increase the joint efficiency by increasing the rotational speed of the tool, but achieved a maximum efficiency of about 72%. He observed that this procedure led to the formation of large defects, rough surfaces, and the burning of the polymer. As a result, the voids and cavities formed during the conventional FSW were removed and defect-free joints with smoother surfaces were achieved. The welds done using the same welding parameters but preheating the polymer to a temperature of 80 °C, presented a joint efficiency of around 72%, proving that excessive heating is harmful.

Preheating large plates of polymer is difficult to do and maintain during the welding so, the supply of heat through a heated tool is a more practical and quicker solution. The heating of the tool is usually done by induction or by applying electrical resistances inside the tool. This technology gives different results in terms of strength of welds in PE and PP, but, as the results are scarce, they are presented together.

A new FSW hot tool technique named induction friction stir welding (i-FSW) was developed and presented by Vijendra and Sharma [35]. They observed that when no external heat was supplied the maximum joint efficiency achieved was about 50% for a rotational speed of 3000 rpm and a welding speed of 50 mm/min, which means a w/v ratio of 60 rot/mm. It is concluded, therefore, that the new tool design and the supply of heat bring improvements in the quality and strength of the welds performed by i-FSW. Despite the maximum joint efficiency reached, about 100%, the experiments were conducted in bead-on-plate (BOP) configuration, which reduces the likelihood of root defects forming.

This tool was created in order to avoid major changes in the conventional tool design. The results demonstrated that the use of this tool heated at 110 °C brings advantages to the process, since the tensile strength and elongation of the welds were always superior to those obtained by the non-heated tool at the same rotational speed. The welds obtained without a heated tool showed large propensity to form cavities within the seam and irregular surfaces, with pronounced burr defects, while the welds obtained with the heated tool presented few or no defects and a better surface finish. Due to the similarity of the results obtained in terms of strength, both rotational speeds are suggested for future studies.

A hot tool with a stationary shoulder is a combination of two FSW techniques and it was the welding technique that allowed the highest values of joint efficiency for both materials. The most common tool used in this technique is sometimes named hot shoe. The hot shoe tool was a solution found to solve the problems related to the formation of voids within the weld seam and also to improve the mixing of the molten material in the FSW of polymeric materials [36]. With the implementation of the hot shoe in the process, the cooling and solidification occurred under pressure in a longer period.

In this experiment, different rotational speeds and welding speeds were used and different shoe temperatures were also tested. By increasing the tool's temperature, this defect was removed. Joint efficiencies above 90% were achieved with tool temperatures of 110 °C and 140 °C, and rotational speeds of 1600 rpm and 1250 rpm and welding speed of 25 mm/min. **Figure 3** shows that the tool with heated stationary shoulder performs welds with joint efficiencies higher than the majority of those obtained with the other welding processes mentioned above.

In another study, using the same material (10 mm thick HDPE) and welding process (hot shoe), Azarsa and Mostafapour [37] investigated the effect of heating temperatures between 70 °C and 150 °C for several tool rotational and welding speeds on the weld's quality. They observed that at rotational speeds above 1400 rpm the polymer began to burn in the preliminary tests. Below 700 rpm, the heat generated was insufficient to ensure adequate material mixing, and wormhole defects were formed. At welding speeds above 100 mm/min, the quality of the weld was bad, and the weld crown became filled with deformations and external voids.

According to this researcher, the advantage of using this tool is that the temperature can be maintained without changing other welding parameters. Tensile strengths and elongations above 90% were achieved with different welding conditions. A maximum joint efficiency of 96% was achieved with a rotational speed of 565 rpm, a welding speed of 24 mm/min, which means w/v ratio of about 23.5 rot/mm, and a tool temperature of 150 °C. On the other hand, by using the Taguchi method and the analysis of variance, the best parameters found were a rotational speed of 950 rpm, a welding speed of 24 mm/min, which means w/v ratio of about 39.6 rot/mm, and a tool temperature of 150 °C.

The conclusions presented in the current work for PE and PP are similar to those drawn for other materials such as ABS or PA6, although the number of studies available in the literature is much smaller. The study performed with and without a heated tool achieved a joint efficiency of 75.5% and 68%, respectively. [38] butt welded 16 mm and 8 mm thick plates of PA6 and achieved joint efficiencies of 32% and 55% with conventional FSW, respectively. These results reinforce the conclusions obtained for PE and PP that hot tools with stationary shoulders are better to weld polymeric materials and that the influence of parameters often neglected, such as axial force, should not be underestimated.

[39] proved experimentally in PC welding that the use of underwater friction-stir welding (UFSW) reduces the heat input in the process, which decreases structural changes in the polymer and the formation of defects and increases the tensile strength of the welds. Furthermore, they did the thermo-mechanical modelling of the process. Other new technologies have been developed recently, based on FSW, but mainly for dissimilar joining, as is the case of fed friction stir processing (FFSP) in AA6062/PMMA bindings [40]. The authors argue that with the introduction of alumina nanoparticles during FFSP the tensile strength of these bonds can be increased up to 14%.

4. Discussion, Conclusions, and Future Work

FSW with conventional tools makes welds with a satisfactory tensile strength, even if most of the authors reported a maximum joint efficiency of under 75%. Joint efficiency increases with the tool rotational to traverse speeds ratio (w/v) for the conventional process, although it is also affected by other process parameters. A high w/v ratio does not in itself guarantee that high strength welds are obtained. The rotational speed of the tool must be above a certain limit, but excessive rotational speeds can degrade the polymer.

The use of stationary shoulder tools allowed better weld surface finish, fewer defects, and higher joint efficiency. The use of external heat sources makes welds with a greater tensile strength possible, as a result of the improvement in the material mixing and the removal of root defects and cavities in the retreating side of the welds. The technique of preheating the polymers to be welded improves the resistance of the welds, but it is impractical, especially for long welds. Conventional heated tools also provide a significant improvement in joint efficiency, but the results available are scarce and, in our opinion, the detrimental effect of shoulder rotation is difficult to overcome.

The use of heated stationary shoulders allows the production of welds with the highest joint efficiency because they join the benefits of the application of external heat and of non-rotating shoulder. The current authors doubt that the system is effective for high polymer thicknesses, due to the reduced thermal conductivity of the polymers. Its analysis reinforces the idea that the FSW techniques with Heated Stationary Shoulder tools provide welds with better quality and joint efficiency. However, as mentioned above, due to the low thermal conductivity of polymers, the heat input to the pin (and not just to the shoulder) must be considered in the future, especially for welding thicker plates.

Figure 3 and **Figure 4** show that the mechanical behaviour of welds in PE and PP is markedly different for any of the FSW technologies and parameters used, which suggests that this is due to the different physical and mechanical properties of the polymers. This study also shows that, in the FSW of polymers, there are several features that are still poorly studied, requiring further analysis. The effect of the plunge depth or axial force on the morphology and strength of the welds was not discussed in most of the works and needs further research. The relationship between the physical properties of the polymers and the optimal welding parameters needs careful analysis.

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