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Technical Paper

Shoulder design developments for FSW lap joints of dissimilar polymers

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ABSTRACT

This paper describes the process of developing a stationary FSW tool for welding thin plates of dissimilar polymers. Previous FSW research seems to be still far from the type of systematic engineering approach that leads to consistent results, in particular for polymeric materials and especially for lap joining of polymers. This study is focused on the development of welding tools, aiming at sound and robust friction stir welding of dissimilar polymeric materials in lap joint configuration. Different materials and geometries have been tested in order to analyse quality of the welds and appearance. It has been verified that stationary shoulders made out of polymer materials give the best result. The welds produced with this tool improved the welds surface quality and strength significantly. The use of the proposed tool showed to improve the stability in the axial force magnitude during the welding procedure in comparison with a conventional FSW tool.

1. Introduction

Friction stir welding (FSW) technique is one of the most promising joining methods, which accounts for the considerable development efforts the technique has gone in the last decade. FSW was introduced to join lightweight alloys that are difficult to weld using conventional techniques. Although some immediate benefits of the technique were planned in advance and built into the technique, such as the high-quality finishing of the welded part, surprising side benefits such an improved resistance to crack propagation relative to the base material were found that further increased the interest in the development of the tool.

Given the recent increase in industrial demand for lightweight design structures [1], novel joining methods are required to tackle new challenges, such as multi-material joining. FSW is one of the most attractive methods in this regard, due to its solid-state philosophy and the ability for full automation. Even though the FSW technique was originally developed for joining aluminium alloys [2], the method is presently being studied to weld other materials such as polymers, metallic materials, copper [3,4] and even joining dissimilar materials [5].

Among all the advantages of the FSW technique, the following stand-out clearly due to their potential impact in industry:

- Being a solid-state welding process; the generated heat for this process is about 70% to 90% the base material's melting point [6];
- It is applicable to components of a large range of thicknesses with accurate reproducibility [7,8];
- Doesn't require post-welding processing;
- Due to the low amount of heat generated, components with high mechanical properties, low distortion and residual stresses are obtained;
- It is an inherently environmental-friendly process because no filler material, toxic fumes or shielding gases are employed or generated;
- Traditional welding defects such as hot cracking and porosity are not an issue [9,10].

The FSW process itself is based on the heat generated by friction between the FSW tool and the base material surface [11]. Conventional FSW tools consist of a rotating pin attached to a shoulder, which penetrates the parts to be welded and traverse along the weld line, as demonstrated in Fig. 1. The generated heat leads to

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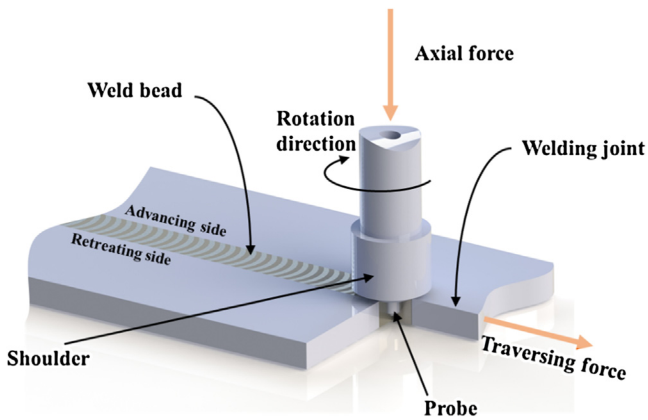

Fig. 1. FSW schematic representation.

extreme stirring, reaching a state in which plastic deformation occurs and is appropriate for welding [12].

During the welding process, the rotating probe positioned inside the weld line causes the material to become soft and enables it to flow and be stirred. On the other hand, the rotating shoulder is located on the surface of the plates, which generates frictional heat and avoids the material flash leakage out of the seam, providing a smooth surface. As illustrated in Fig. 1, the weld bead is divided in two areas: in the advancing side the tool rotational direction is the same as the welding direction; the retreating side corresponds to the side where the tool welding direction is opposite to the tool rotational direction. In order to weld the two plates, the soft material is transferred with the probe, along with a forging force caused by the shoulder.

The consumption of lightweight materials, such as polymers and composites has been growing dramatically in a diversity of industrial and engineering applications, due to the improvement in strength-to-weight ratio of those materials [13]. Consequently, polymers and composite materials joining are the new challenges the technique needs to address. Just as FSW proved its advantageous for metallic materials, a breakthrough in FSW polymers joining is currently sought after.

Welding of polymeric materials can be categorized into the following classifications [14]:

(1) Mechanical movement to generate heat: vibration welding; friction welding; ultrasonic welding;
(2) Additional heating technique: hot gas; hot plate; implant and resistance welding.

For all the above welding methods, the first step is to generate enough heat in order to reach the plastic deformation stage, then the nearly-molten material will bond together under pressure and the final stage will be to let the material cool down [15,16].

Authors such as Strand claim that polymer FSW is not an absolute solid-state process [16]. Due to different molecular weights, polymers do not have a particular melting point, but a melting range. In view of this fact, shorter polymer chains can reach their melting point during welding, whereas longer chains may not. Consequently, the soft material will be the mixture of molten material with a relatively small amount of solid material. However, there will be enough molten material to let the material flow easily.

The main difficulty for FSW polymers is the lack of frictional heat generated through contact between the rotational tool and the base material. This applied friction should generate the adequate heat in order to increase the material temperature near its melting point. For FSW of Aluminium alloys, this task is implemented by a rotating shoulder touching the surface, which generates enough heat to stir the material together. Therefore, the shoulder has an essential role in this process and is one of the parameters that plays a considerable effect on the weld strength, as well as the welding surface. It is worth mentioning that a good welding surface is normally a positive indication of a high joint quality.

Some studies realized [17] that it is difficult to obtain a good surface quality and high mechanical properties of the welded part with traditional FSW tools in polymers welding. Due to the low melting point, hardness and thermal conductivity of polymers [18], these materials can reach their melting point quickly, thereby demanding new development which are still not available, particularly those that concern development of tools. Since tool plays a critical role in this technique, development of sufficient FSW tools for polymers is considered a topic that needs further investigations.

Although FSW of thermoplastic composites is a challenging engineering field, only a restricted number of researchers attempted welding polymers using FSW [19]. Tensile strength of the produced welds is very low and mostly affected by the pin geometry and welding speed, which brings about the formation of defects in welds on Polypropylene (PP) composites reinforced with 20% carbon fibre (CF). PP and its composites are typically joined by bonding or welding methods [20,21]. In a previous investigation [8], a comparison between the common welding techniques and FSW of PP has studied, clearly showing that the mechanical properties achieved by FSW are higher than the ones obtained with other techniques. Moreover, they established that the roughness of the weld seam is higher than that of the parent material and the weld strength is lower than half the one of the base material. The generally accepted explanation for this behaviour is based on the generated heat distribution at the weld seam and its surrounding areas, which leads to a non-uniform crystallization rate of material in those areas. In another study [22], it was realized that for FSW of polymers, the traditional tools push the soft material out of the weld bead. This material loss is responsible for poor bonding formation, leading to low tensile strength and poor mechanical properties. Up until recently, the most common tool used with polymers FSW is *hot shoe*, developed by Nelson *et al.* [22]. This tool consists of a static shoulder with a heater and a thermocouple inside, and a rotating probe to stir the almost molten material. This tool traps the material inside the weld bead, promoting the formation of a good surface quality. More recently, new tools have been developed for welding high density polyethylene by Kiss and Czigány [8]. The tool developed consists of a hot shoe with a threaded pin. However, due to the low thermal conductivity of polymers, it was detected that mechanical properties of the obtained welds are highly dependent on the generated heat. In another study [23], a heated shoulder with threaded pin was used for butt joining ABS plastics, and a good weld appearance was obtained with this tool.

The work presented in this manuscript focuses on the effect of different tool designs on lap joints of dissimilar polymers: Polystyrene and Polypropylene. Furthermore, this study demonstrates the advantages of using a stationary shoulder for welding polymeric materials, and suggests a possible path to prevent the formation of defects and achieve high quality welds.

2. Experimental procedure

Friction stir welding experiments were implemented on a 3-axis CNC machine. The welds were produced using a position control method with a sensorized clamping system for load acquisition, which is shown in Fig. 2. Polymers behave differently than aluminium and tend to buckle easier under pressure, which demands a more sophisticated clamping system. The designed fixture is instrumented with four load cells connected to data acquisition equipment. The data is acquired and manipulated with a dedicated

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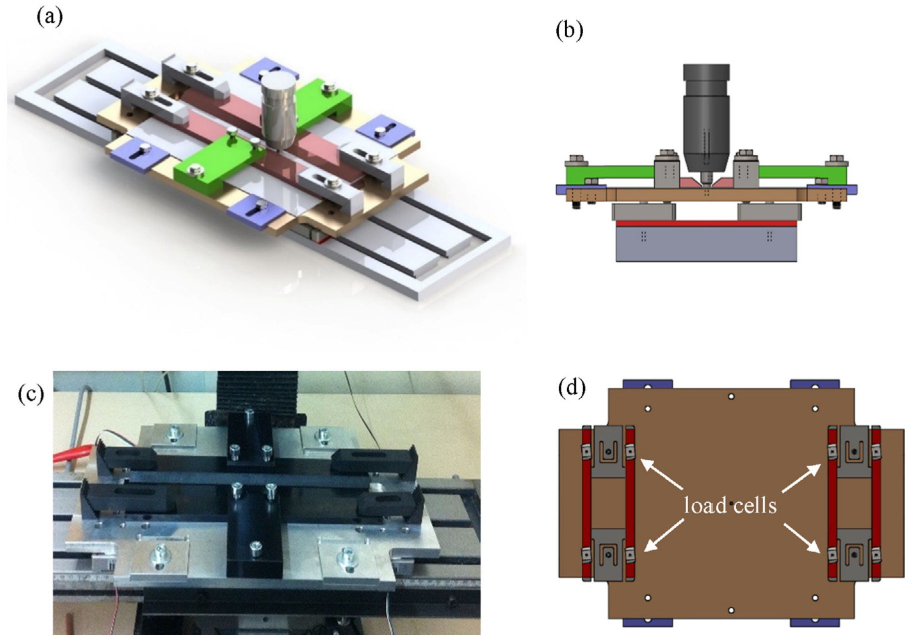

Fig. 2. Fixing system: (a) isometric view, (b) front view (c) real image of the fixture on the CNC table and (d) detail of the load cells configuration.

Table 1
Material specifications.

Material	Dimensions (mm^3)	Tensile strength (MPa)	Melting range (°C)	Density (kg/m^3)
Polypropylene (PP)	100 × 80 × 1.5	28	163	910
Polystyrene (PS)	100 × 80 × 2.6	50	180–280	1040

LabView™ code developed in our laboratory that enables the observation and registration of the applied force during welding.

Rotational speed, traverse speed and the tool geometry are parameters which can most prominently affect the weld strength. From these parameters, and based on a set of preliminary experimentations for FSW of polymers, it was verified that the tool geometry plays a significant role on the joint overall quality.

Dissimilar polymer materials and thicknesses have been used for the lap joints produced in this work. Table 1 shows the characteristics of the materials which have been used.

Since this study is focused on the development of a suitable FSW tool for polymers, and since no similar study can be found in the literature, different tool designs and dimensions were analysed in an iterative path, Fig. 3. The new tool designs were developed using the following parameters ranges: welding speed 10 mm/min to 70 mm/min, pin length 2.8 mm to 3.6 mm, and rotational speed 800 rpm to 3000 rpm, depending on the tool being used.

Different probes and shoulders have been developed in the course of the current work. The initial tests were performed using a conventional rotating shoulder design with different diameters. Afterwards, a rotational probe with a stationary shoulder study was carried out. In order to avoid the shoulder rotation, a tool incorporating bearings was designed. Stationary shoulders with different materials have been developed and analysed. Polycarbonate, teflon, aluminium, wood and brass stationary shoulders have all been tested with different degrees of success, Fig. 3.

In the stationary shoulder solution, ball and thrust bearings inside the shoulder let the rotating probe rotates with spindle preventing the shoulder to spin. One of the main challenges of using a stationary shoulder is to prevent the injection of the soft material inside the shoulder and bearing, and it is one of the main reasons that lead shoulders to fail, in particular during long runs. In order to avoid this problem, different sleeves have been used around the pin. Ejected material from the weld seam can lead to root defects in the retreating side of the weld, which is not acceptable and needs further study.

The strength of the welds was determined in tensile testing performed in an Instrom ElectroPuls™ machine, Fig. 4(b), using a 2 mm/min loading rate. Specimens were cut out of the weld seam with a proprietary tool developed for this study, Fig. 4(a) and (c).

3. Results and discussion

The main objective of the presented study is the development of new FSW tools capable of achieving quality welds with acceptable surface quality. The tools developed in the course of the present

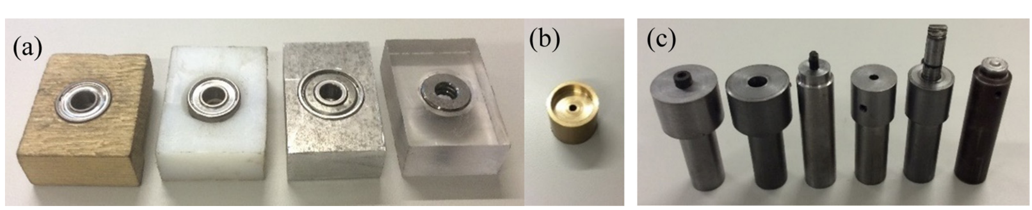

Fig. 3. Some of the FSW tools developed: (a) from left to right, wood, teflon, aluminium and polycarbonate stationary shoulders, (b) brass stationary shoulder and (c) rotating shoulders with different diameters.

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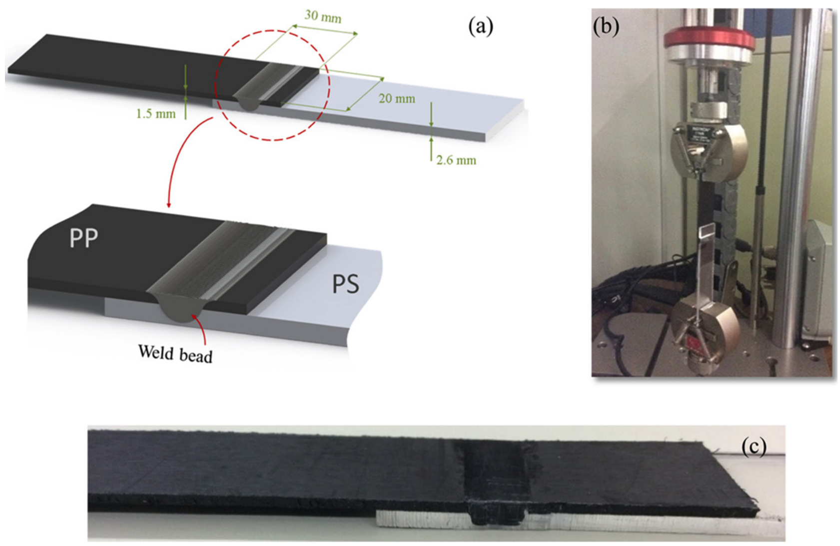

Fig. 4. (a) Schematic of overlap area of the specimen, (b) tensile stress test and (c) specimen ready to be tested.

study have all been tested for a number of probe length, probe diameter, and rotational and traverse speeds. Peel tests were performed in order to evaluate the weld bead materials configuration for the different probe geometries. For those that led to an improved stirring, tensile tests and analysis were carried out.

One of the most important characteristics of a quality weld is a good surface quality. The more similar the weld is to its parent material, the more it retains the parent material's characteristics. The amount of heat generated by friction is directly dependent on the used tool. Geometric features of the pin and shoulder, tool penetration and diameters are the main factors which directly affect the material flow and heat generation during welding [24]. Using a stationary shoulder, all the frictional heat is generated by the pin. In previous investigations, in order to compensate for the lack of generated heat, extra heating *hot shoe* systems have been employed. For this research, different pins and shoulders have been created and tested without any extra heating on the plates in order to observe the effect of the different tools, particularly on the resulting surface quality.

3.1. Conventional shoulder

The most popular tool used in FSW consists on a probe rotating together with the shoulder. The shoulder has the main role of generating heat due to the friction between the shoulder and the top surface of the workpiece. The direct effect of the generated frictional heat can be observed on the weld width. Nevertheless, depending on the parent material, insufficient heat can prevent proper joining or, heat overflow can lead to partial melting. Partial melting will modify the material properties as well as bond the melted material to the tool surface. In order to achieve strong welds, the ejected material from the weld seam has to be kept at a minimum.

An initial 8 mm diameter shoulder has been tested with a 3 mm squared pin. As can be seen in Fig. 5, the material was not mixed and a damaged surface occurred for all the welding parameters.

Since the lack of heat often leads to insufficient bonding, larger shoulders with 10, 15, 20 mm diameters, have been tested. Due to their larger diameter, additional heat was generated, but it was still not possible to obtain appealing weld surfaces. Although good surfaces were obtained at the initial length of some welds, for longer welds the shoulder literally melted all the material causing it to slip and stick around the probe and shoulder, as it can be seen in Fig. 6.

It was therefore concluded that a rotating shoulder design is not a good option for welding polymers. The produced weld bead presents a very rough surface and flash and root defects occurred along the weld line.

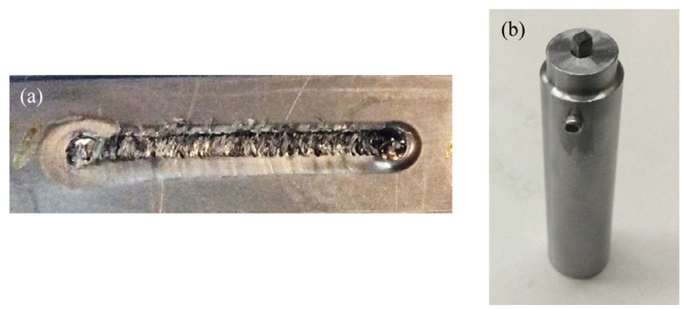

Fig. 5. (a) Welded parts with 3 mm conventional FSW tool and (b) FSW tool with 3 mm squared probe and 8 mm rotating shoulder.

3.2. Stationary shoulder

Since, the results obtained using conventional shoulders were not satisfactory, a stationary shoulder design was developed to evaluate the weld bead surface quality. Using a stationary shoulder, the results were better than those obtained with the previous rotating tool design. A schematic design of the stationary shoulder developed is presented in Fig. 7.

However, without the rotating shoulder, the pin generates all the heat, from the rotational movement. Most of the previous

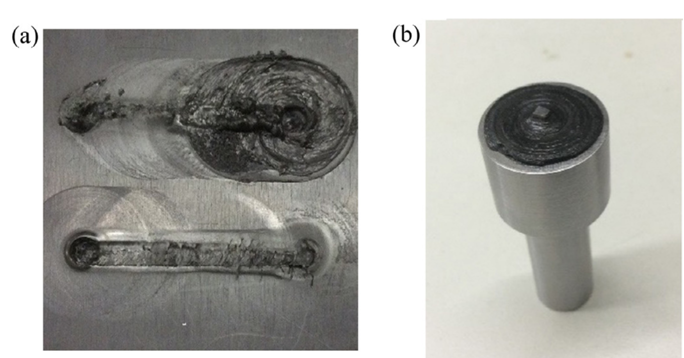

Fig. 6. (a) Welded part with 3 mm squared probe and 20 mm rotating shoulder and (b) PP material stuck around the probe and shoulder surface.

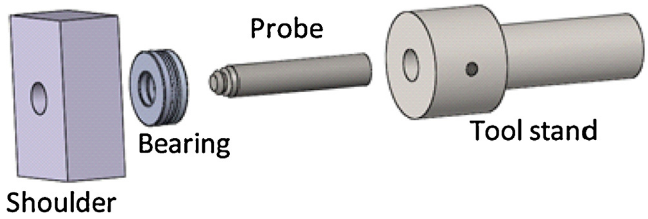

Fig. 7. Stationary tool schematic representation.

studies in this topic, used extra heating from within the shoulder, in order to compensate for the inherent lack of heat [16].

A stationary shoulder made with wood and a ball bearing was tested first, and the initial results were promising, as it can be seen in Fig. 8(a). However, some defects were still present. Wood presented deformation under pressure, which caused defects on the retreating side of the weld bead. Nevertheless, it was possible to avoid the flash defect, characteristic of a stationary shoulder design. The stationary shoulder pushes the material down and does not let the soft material go outside the bead, letting it cool down under the applied pressure, and preventing the appearance of such defects.

In some welds, a lack of the PP material in the weld line was observed which caused root defects. Usually, the missing material was found inside the shoulder and bearing, cf. Fig. 9. Under pressure, soft materials go upwards around the pin, then inside the bearing and damage the bearing. Despite promising results, it was realized that a stationary shoulder design needs additional improvements in order to achieve defect free welds.

In order to overcome the difficulties found with the wooden shoulder, different materials were tested to evaluate the effect of the shoulder material on the weld surface. Using an aluminium short shoulder, the surface appearance was relatively good, but not as smooth as required, Fig. 8(b). A long aluminium stationary shoulder was consequently tested with the ability to heat up the plates to be welded in advance, although no obvious improvement has been noticed.

Using a Teflon shoulder allowed the improvement of the weld surface quality significantly. However, in some circumstances, the area around the probe suffered large deformation as a consequence of the pin temperature. This shoulder deformability usually occurs for long welds with a low transverse speed, Fig. 8(c). Any deformed shoulder can cause material loss inside the weld seam leading to further defects. The polycarbonate shoulder, Fig. 8(d), presented a similar weld quality as the Teflon, but with lower deformability under different welding circumstances.

Finally, a fully brass stationary shoulder has been tested as shown in Fig. 10, but due to its high thermal conductivity, a large amount of heat was accumulated inside the brass volume instead of heating up the bead, and consequently the weld nugget suffered from lack of sufficient heat generation.

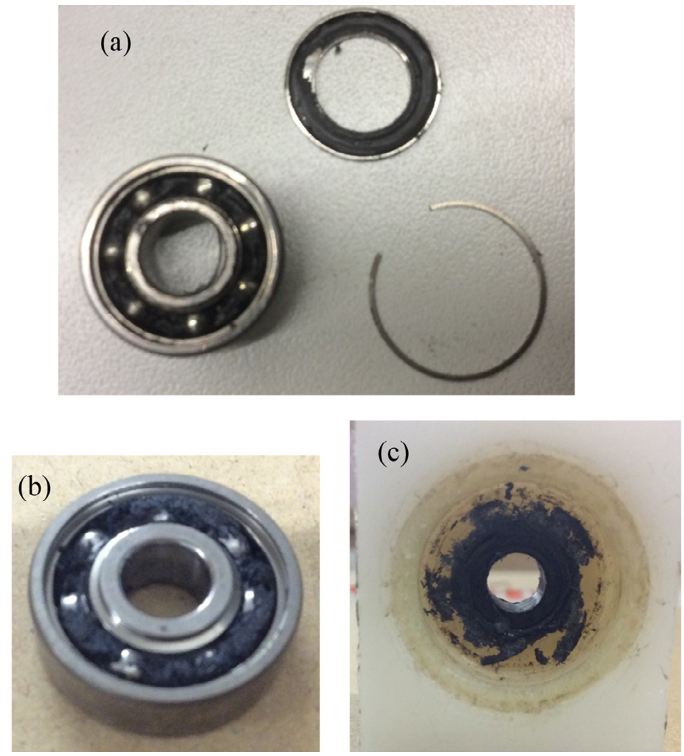

Fig. 9. Tool related issues. (a) set of damaged tool parts; (b) PP material inside the ball bearing and (c) PP material inside the shoulder, around the probe.

This functional procedure enabled the choice of the best materials for the shoulder in Polycarbonate or Teflon although there still remains a tendency for the materials to move up the bearing, causing a lack of material in the weld bead. An improved design was thereby developed to address this issue.

In order to avoid material loss, brass and copper sleeves with lubrication free capability were tested. Copper, alone as a sleeve, heats excessively and deforms the Teflon around the pin. Brass can have the same problem, but in some cases, the brass sleeve rotated with the pin under pressure and caused the shoulder to melt around the pin. It was concluded that the most effective solution is to have a brass sleeve inside a copper sleeve, Fig. 11. It gives one more degree of freedom and even though the brass sleeve rotates, it does so inside the copper sleeve and will not damage the shoulder. This

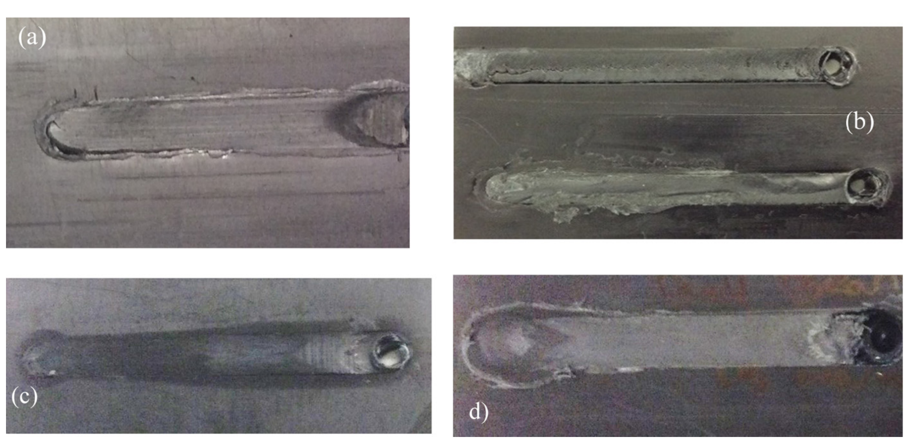

Fig. 8. Welded part with: (a) wooden stationary shoulder; (b) aluminium stationary shoulder; (c) teflon stationary shoulder; (d) polycarbonate stationary shoulder.

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Fig. 10. (a) Weld seam created by brass stationary shoulder and (b) Stationary shoulder fully made by brass.

method can easily increase the life of the shoulder and eliminates defects such as lack of material in the weld bead.

3.3. Probe

With the absence of a rotating shoulder to assist in the generation of heat, the probe plays an even more important role in order to produce heat and stir the soft material together. To weld polymeric materials, probes should have grooves or threads to allow the softened material to flow simply with excessive amount of turbulence. Without grooves the material sticks on the advancing side of the weld and will not stir sufficiently. Threads have the same effect as grooves, with improved friction followed by additional heat. The direction of the thread should be opposite of the spindle rotation direction, otherwise the threads will move the soft material outside the weld bead.

Three different probe geometries were tested: cylindrical with two flat surfaces, triangular and squared probes have all been

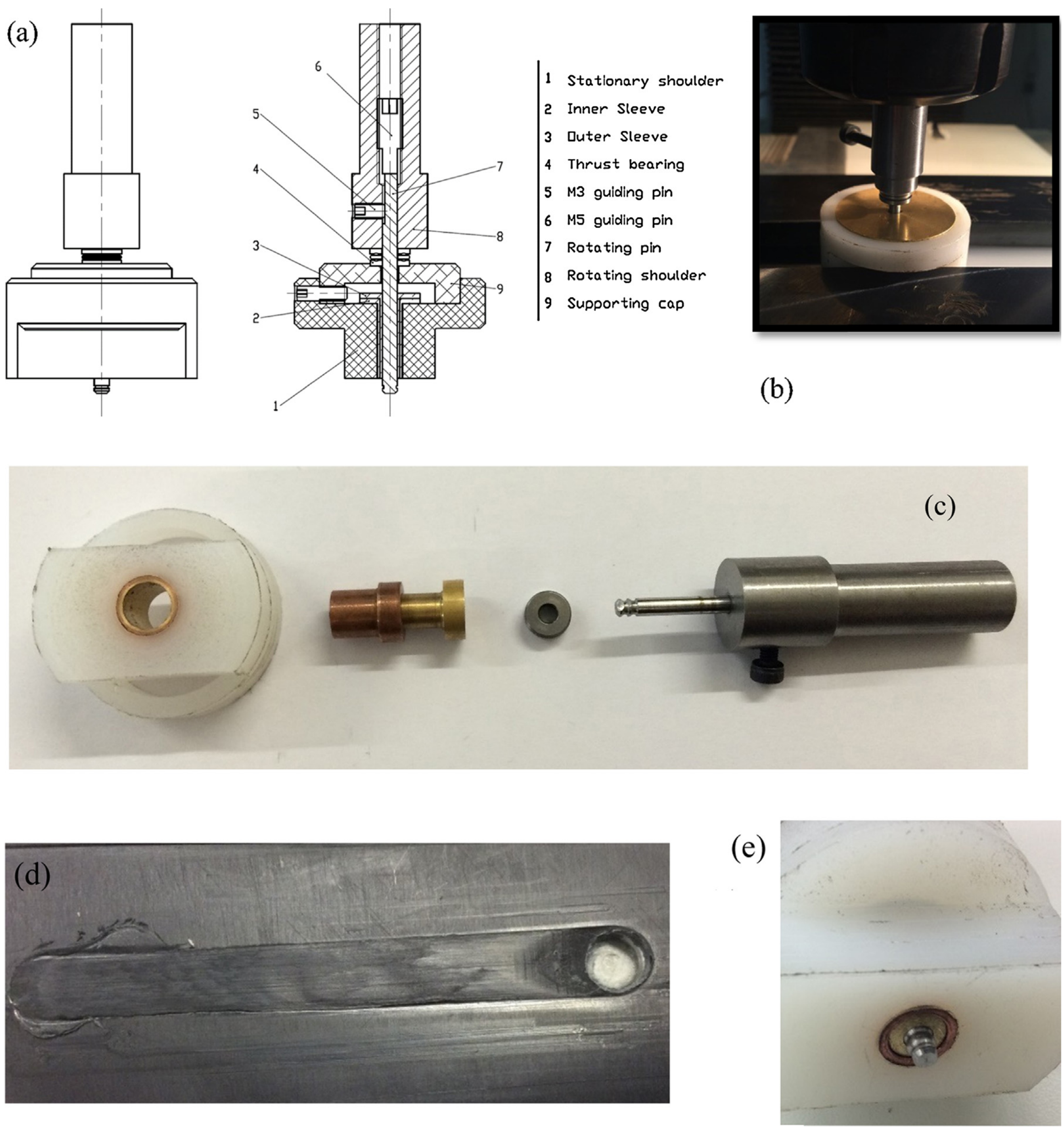

Fig. 11. Newly developed FSW took with stationary shoulders (a) final design drawing, (b) actual tool during welding, (c) teflon stationary shoulder with brass and copper sleeves, (d) welded part with teflon stationary shoulder and 6 mm probe and (e) overall view of the developed FSW tool.

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Fig. 12. Set of different probes tested.

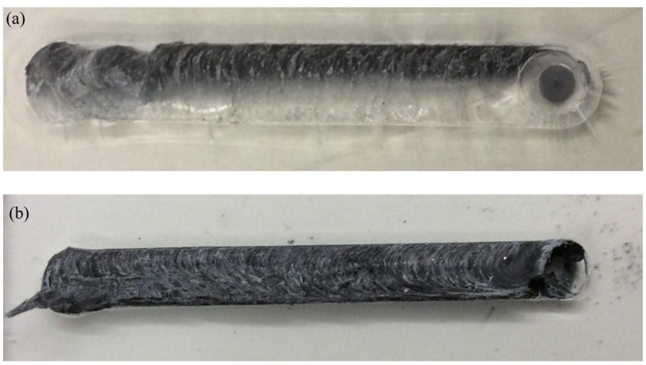

Fig. 13. Differences between non-threaded probe (a) and threaded probe and (b) after the peel test.

investigated in this study. A set of different tools tested, geometry and diameter, is presented in Fig. 12.

These probe geometries were selected as a result of their increased angle of attack and consequently their ability to generate more heat. The resulting difference between non-threaded and threaded pin can be seen in Fig. 13. While in Fig. 13(a) both translucent and black materials are easily perceptible in the weld line, in Fig. 13(b) they are not.

Probe diameter and length are other effective factors on the weld quality that should be considered. If the difference between thickness of the plates and probe length is out of range, the second plate, which is PS, will not be joined properly due to lack of penetration, and defects may occur in the weld bead. Likewise, the use of a short probe may result in insufficient heat generation and improper material stirring. The investigated pins have a range of 2 to 3.6 mm in length and 3 to 7 mm in diameter.

3.4. Axial force

Because axial force plays a critical role in FSW process, the quantification of the applied force for different types of tool design can help understand their behaviour during the welding operation. It was verified that the axial force is a function of the tool being used. Due to the large area of the stationary shoulder, when the shoulder contacts the plates the applied force increases significantly, but when the tool advances the force decreases and stabilizes even using a position control system. This behaviour can be explained by the effect of temperature on the material hardness. The axial force for Teflon stationary shoulder with 3 and 7 mm triangular probes and different welding speeds is shown in Fig. 14. Furthermore, the use of threaded pins will reduce the axial force during

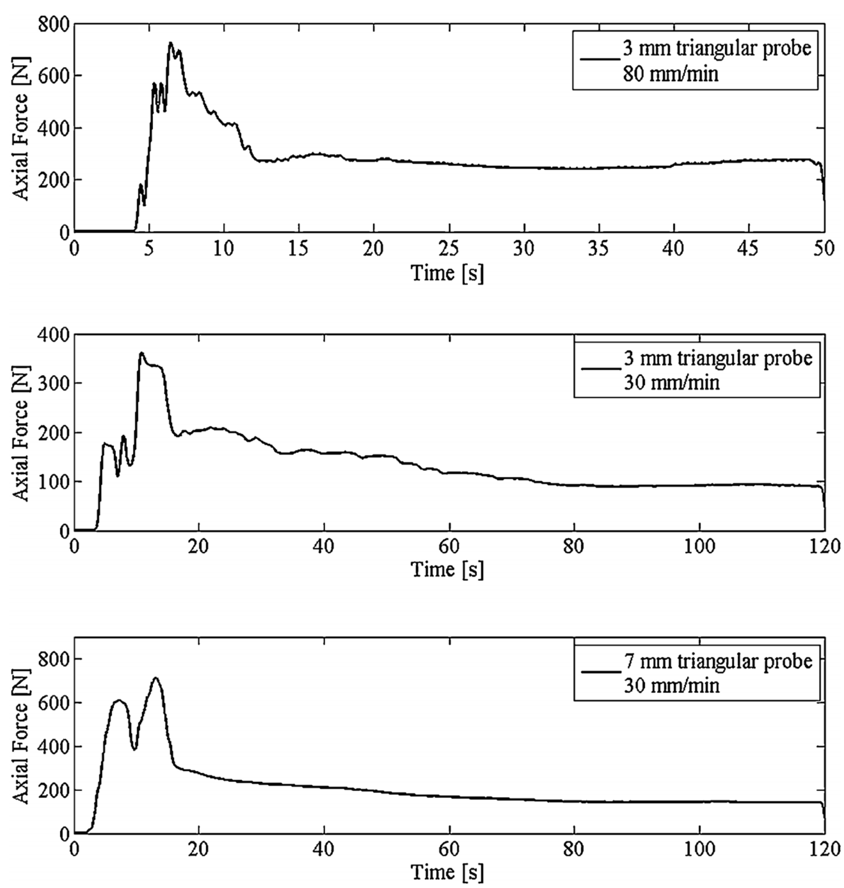

Fig. 14. Stationary shoulder axial force during welding.

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Table 2
Loads before failure for tested specimens*.

Specimen ID	Shoulder penetration [mm]	Pin length [mm]	Traversing speed [mm/min]	Rotational speed [rpm]	Maximum Load [N]
R3	0.1	2.05	50	1700	83.3
S3	N/A	3.40	30	1800	117.0

* All the tests were performed with 3 mm probe diameter and overlapped area of 600 mm².

welding. Using a conventional rotating tool an unstable loading is verified when a position control system is used. Axial force using a conventional FSW tool was found to be defined in three main zones or sections, which can be distinguished by different force peaks and slopes. While the first zone is characterized by a low force unstable state, the second presents a high slope followed by the maximum axial force, or peak, decreasing rapidly to the third section where it remains relatively stable and constant.

3.5. Tensile strength

Lap shear tests were performed for both stationary and rotating shoulder joints to quantify the tool effect on the weld strength. Table 2 shows the tensile strength results of specimens welded using a conventional tool with a 3 mm squared probe (R3) compared to those welded using the Teflon stationary shoulder (S3). Two specimens were cut for each set of welding parameters, and the maximum loads in the Table 2 are their mean values. The results demonstrate that the tensile strength of specimens obtained using the stationary shoulder tool can have more than 40% strength when compared to those achieved with a rotating shoulder. Several welding parameters have been tested in order to achieve the strongest weld using conventional tool. The strongest weld specifications made by rotating shoulder can be seen in the first row of the Table 2. The obtained results using stationary shoulders were achieved without parameters optimization. Due to the low thermal conductivity of polymers and insufficient heat generation on the retreating side of the welds, during the tests all the specimen failed from the retreating side. The tensile strength of the joints obtained using a stationary shoulder is approximately 50% of PP base material (28 MPa tensile strength, Table 1).

4. Conclusion

A new design for polymeric material FSW was developed and presented in the present manuscript. The effect of different tool design, Table 3, shoulders and pins, on the weld quality was evaluated, and an optimized tool design for welding polymers was developed. Using a conventional FSW tool with different geometries and parameters did not enable production of sound welds due to flash defects around the weld bead. Using a stationary shoulder design the following conclusions can be drawn:

- The stationary shoulder enabled stronger welds with good surface quality.
- A Teflon polymeric material stationary shoulder proved to be the best option, resulting in superior surface quality when compared to aluminium, brass and wood shoulders.
- Pins must have grooves in order to properly stir the material.
- Using stationary shoulders, the applied force is kept constant during the operation, the same behaviour cannot be found using rotating shoulders.
- The best results were achieved using two sleeves for the stationary shoulder. An outer sleeve made of copper gives an additional degree of freedom for the brass sleeve as well as absorbing heat in order to avoid damaging the shoulder.
- Functional lifetime of the plastic stationary shoulders will be increased using two sleeves around the pin.
- The retreating side of the weld suffers from lack of proper stirring and heat generation.
- In order to compensate the lack of heat by using stationary shoulder, the rotational speed of the tool must be increased.

Table 3
Overall view of the tested shoulders and probes.

Rotatory shoulder diameter (mm)	Stationary shoulder material	Probe geometries
8	Polycarbonate	Cylindrical
10	Teflon	Threaded cylindrical (M6, M3 screws)
12	Wood	Triangular
15	Aluminium (short and long)	Triangular with groove
20	Brass	Square
	Copper	Conical with two flat surfaces

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