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Effect of friction stir welding parameters on morphology and strength of acrylonitrile butadiene styrene plate welds

N. Mendes [a], A. Loureiro [a], C. Martins [b], P. Neto [a,*], J.N. Pires [a]

[a] CEMUC – Universidade de Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
[b] IPC/I3N – Universidade do Minho, Campus de Azurém, 4800-058 Guimarães, Portugal

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ABSTRACT

The aim of this study is to examine the effect of main friction stir welding (FSW) parameters on the quality of acrylonitrile butadiene styrene (ABS) plate welds. Welds were carried out in a FSW machine, using a tool with a stationary shoulder and no external heating system. The welding parameters studied were the tool rotational speed which varied between 1000 and 1500 (rpm); the traverse speed which varied between 50 and 200 (mm/min), and the axial force ranging from 0.75 to 4 (kN). The major novelty is to study the influence of the parameter axial force on FSW of polymers. Produced welds have always a tensile strength below the base material, reaching the maximum efficiencies of above 60 (%) for welds made with higher rotational speed and axial force. Good quality welds are achieved without using external heating, when the tool rotational speed and axial force are above a certain threshold. Above that threshold the formation of cavities and porosity in the retreating side of the stir zone is avoided and the weld region is very uniform and smooth. For low rotational speed and axial force welds have poor material mixing at the retreating side and voids at the nugget. For this reason the strain at break of these welded plates is low when compared with that of base material.

1. Introduction

Friction stir welding (FSW) was initially developed by Thomas et al. [1] in the early nineties for joining soft metals, as aluminium alloys such as those of series 2XXX and 7XXX, which were generally considered unweldable or difficult to weld at that time. The weld seams produced by this method are free from defects such as cracks or porosity; it also produces low distortion as compared to fusion welding processes. This makes FSW a very attractive welding process. The traditional FSW process consists of a rotational tool, formed by a pin and a shoulder, which is inserted into the abutting surfaces of pieces to be welded and moved along the weld joint, as illustrated in Fig. 1. During the process, the pin located inside the weld joint, softs the material and enables plastic flow, causing the mixture of materials. At the same time, the shoulder placed on the surface of the seam heats and drags material from the front to the back side of the tool, prevents leakage of material out of the welding joint and smoothes the crown seam to provide a smooth surface. This process is applied mainly to butt and lap weld joints but other joint geometries can be welded.

FSW of polymers is an attractive welding process because of the characteristics conferred to the welded seam. Strand [2] compared the most common welding processes used to join polymers, concluding that FSW is the process where is achieved higher weld strength efficiency. This process enables the production of very highly efficient welded seams with low energy consumption. In addition, relatively low cost is implied, because of its low use of energy, and it does not require the addition of filler materials. Furthermore, FSW does not require skilled professionals, and can be easily automated. Nelson et al. [3] claimed that the traditional FSW tools do not give proper results in terms of weld morphology and tensile strength when applied to polymeric materials. This effect is caused by specific properties of polymeric materials, such as their low melting temperature and low thermal conductivity when compared to metals. In order to overcome these difficulties, several FSW tools with different geometries have been developed. One such example is that created by Strand [4], called hot shoe, which consists of a rotating pin and a static shoe heated by electrical resistances. This system was patented by Nelson et al. [3] and has been used to weld several polymers, namely acrylonitrile butadiene styrene (ABS), high density polyethylene (HDPE), ultra-high molecular weight polyethylene (UHMWPE), polyvinylchloride

* Corresponding author. Tel.: +351 239790700; fax: +351 239790701.
E-mail addresses: nuno.mendes@dem.uc.pt (N. Mendes), altino.loureiro@dem.uc.pt (A. Loureiro), cmartins@dep.uminho.pt (C. Martins), pedro.neto@dem.uc.pt (P. Neto), jnp@robotics.dem.uc.pt (J.N. Pires).

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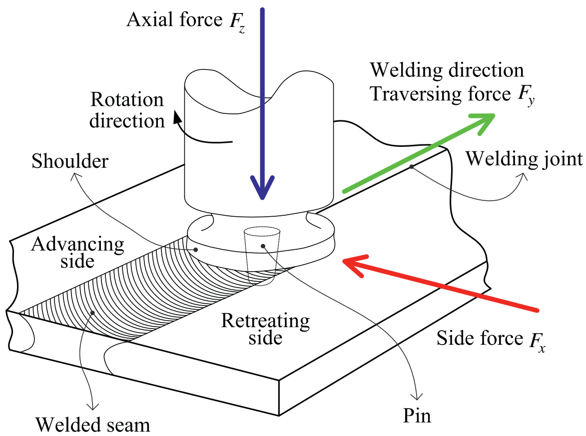

Fig. 1. Representation of the FSW process.

(PVC), polypropylene (PP), polyvinyldenefluoride (PVDF), nylon 6.6 and polytetrafluoroethylene (PTFE). The authors pointed out good results obtained in some welds, in spite of the fact that some welds have presented poor surface finish and few voids. On the other hand, Kiss and Czigány [5] succeeded in joining PP sheets by FSW using conventional milling tools, rotating in the opposite direction to that of milling operations. However, the mechanical properties of the welded seams were poor. Kiss and Czigány [5] presented a new concept of FSW tool: the viblade welding tool consisting of a vibrating blade connected to a vibrating shoe. During the welding process the blade vibrates inside the weld joint while the shoe moves in contact with the upper surface of the weld joint. Although the results of this technique were very good, it presented several drawbacks because of the complexity of the mechanism required to operate the tool, and the short working life of the blade, as concluded by Scialpi et al. [6]. Furthermore, this tool only could be used in welding joints of linear trajectory.

Aydin [7] developed a FSW tool with a larger shoulder, compared to the traditional FSW tool used to weld metallic materials, and a heating system placed at the root of the seam which enables the production of defect-free welds with a basin-like nugget zone. However, the seam welded surface was very rough, with non-aesthetic surface. The same tool concept without heating system has been used in other studies, which are presented below, to investigate the influence of some welding parameters in welded seams quality. The main drawback in the welded seams produced along these studies, as well as in the study carried out by Aydin [7], was bad surface quality of the seams. Bozkurt [8] studied the influence of FSW parameters: rotational speed, traversing speed and tilt angle on high density polyethylene (HDPE) plates. It was concluded that rotational speed is the most influent parameter in the seam quality while tilt angle is the least influent parameter. Payganeh et al. [9] studied the influence of the same parameter investigated by Bozkurt [8] and also the pin tool geometry on a polypropylene (PP) composite with 30% glass fibre. It is reported a taper pin with groove provides better results than other pin shapes. Furthermore, it is shown that larger rotational speed, lower traverse speed and larger tilt angle allows to reach better quality welded seams. In this study is clearly shown that when larger tilt angles are used, better mechanical properties of the welded seams are obtained. As easily understood, when the tilt angle increases, the axial force (Fz in Fig. 1) applied in the welding joint increases too (while the welded seam is being formed). Thus, this study opens the possibility of when higher axial force is used to perform FSW of polymers, higher quality seams are reached. Arici and Sinmaz [10] showed that defects on the seam root can be eliminated by double passes of tool on FSW of medium density polyethylene (MDPE). The influence of the pin geometry in traversing force (Fx in Fig. 1) generated by FSW of polypropylene plates was studied in Panneerselvam and Lenin [11]. The same authors [12] studied the influence of thread direction of the pin in FSW quality of nylon 6. This study concluded that the best seams are obtained when the FSW tool drives material flow towards seam root. These results confirm previous studies presented in Nelson et al. [3]. In recent studies, Kiss and Czigány [13] have proposed the use of a static shoe connected with the milling tool (similar to the hot shoe tool). This new tool has demonstrated promising results, despite not having been adequately explored yet. This is due to the complexity of the tool and the difficulty in controlling certain variables. The tool rotational speed has shown to be the most important parameter in the FSW of PP sheets as shown by Kiss and Czigány [14]. Although other parameters such as tool geometry and size, traverse speed, warming temperature and dwell time also play an important role, as they contribute to heat generation and material flow in the stir zone.

Kiss and Czigány [13] proposed a *K* factor depending on the rotational speed, traverse speed and tool diameter as a key condition for obtaining good quality welds in polyethylene terephthalate glycol (PETG). The *K* factor should range from 150 to 400, with each parameter ranging inside maximum and minimum operational limits. However, the *K* factor does not account for the effect of external heating or the axial force, a parameter which greatly influences the formation of defects at least in FSW of metals. Kim et al. [15] proved that increasing the tool plunge axial force (Fz in Fig. 1) in FSW of aluminium die casting alloy the weld defect size is reduced or removed. In fact, none of the previous studies approaches FSW of polymers taking into account the influence of axial force on the resultant seam. Probably, this is because most of the researchers have used milling machines in their studies, which do not allow either record or control axial force. In robotic welding systems, the axial force must be minimized due to size and cost of robots as it increases with their payload. This axial force can be reduced by increasing the heat generated in the process, adjusting tool rotational speed, and/or adding external heat.

The purpose of this research is to study the influence of rotational and traverse speeds and axial force on the FSW quality on ABS plates. This study takes into account the reduction of axial force required to obtain good quality welds, in order to develop robotic systems adapted to industrial welding of polymers. The effect of external heating is not considered in this stage of the study.

2. Materials and methods

Butt welds were produced between ABS plates of 300 × 80 × 6 (mm^3). Some characteristics of the material are presented in Table 1. ABS is a light material with low glass transition temperature, which has a broad spectrum of applications, such as in the chemical and automobile industries.

A FSW tool consisting of a stationary shoulder and a conical threaded pin of 5.9 (mm) length and 10 (mm) and 6 (mm) in diameter, at the base and at the tip of the pin respectively was developed to perform the welds (Fig. 2). A long stationary shoulder was designed in order to allow heating in front of and behind the pin, although in this set of tests no external heating was applied. The shape of the shoulder is approximately rectangular with a hole in its centre (pin hole). The external dimensions of the shoulder are: 177 (mm) × 25 (mm) and its area is approximately 4396.7 (mm^2).

The welding parameters studied were rotational speed, which varied between 1000 and 1500 (rpm), traverse speed (between 50 and 200 (mm/min)), and the axial force (between 0.75 and 4 (kN)). The selection of these parameters was based on previous tests. Henceforth the welds are designated according to the

Table 1
Main properties of ABS material.

Density (g/cm^3)	Tensile strength (MPa)	Strain at break (%)	Glass transition temperature (°C)
1.04	40.5	50	105

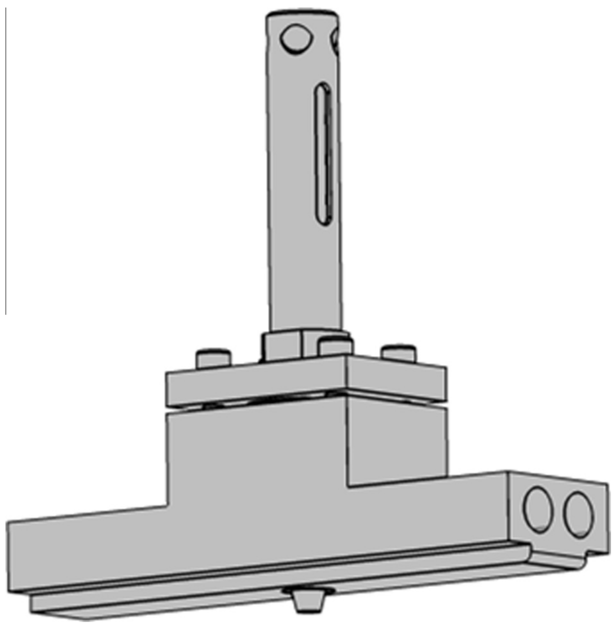

Fig. 2. FSW tool with long stationary shoulder and conical threaded pin.

following convention: letter *R* followed by rotational speed in (rpm); letter *T* followed by traverse speed in (mm/min); and letter *F* followed by the axial force in (KN). Therefore, the designation R1500T200F2 corresponds to a weld carried out with a rotational speed of 1500 (rpm), a traverse speed of 200 (mm/min) and axial force of 2 (kN). All the welds were performed in a FSW machine MTSI-Stir PDS4, which enables the recording of welding data during tests. In order to analyse the effect of tool rotational speed on weld quality, welds were performed with a constant traverse speed and axial force of 100 (mm/min) and 0.75 (KN) respectively, and a variable tool rotational speed of 1000, 1250 and 1500 (rpm). To study the effect of traverse speed, welds were produced with constant rotational speed of 1250 (rpm), axial forces between 2.0 and 3.75 (KN), and traverse speeds of 50, 100 and 200 (mm/min). The effect of axial force on the quality of the weld was investigated for constant rotational and traverse speeds of 1500 (rpm) and 100 (mm/min) respectively, and variable forces of 0.75, 2.25 and 4 (KN), although welds using other forces were also made. Although pressure is a more representative welding parameter than force, it was decided to identify the weld in relation to force. This is because pressure and force parameters are intrinsically related and the majority of the FSW equipment is parameterized by the force parameter and not pressure. In this study, the relation between pressure (*P*) and force (*F*) is given by:

$$P = \frac{F}{A_{\text{shoulder}} + A_{\text{pin cross section}}} = \frac{F}{4425(\text{mm}^2)} \tag{1}$$

where A_{shoulder} is the area of the shoulder and $A_{\text{pin cross section}}$ is the area of the pin cross section at the base of the pin.

For the morphological analysis of the welds, samples were cut out of the weld seams into 10 (μm) thick sections, using a Leitz microtome at room temperature, equipped with a perpendicular slicing glass knife. Optical transmission microscopic analyses were conducted using an Olympus BH transmittance microscope, with digital camera Leica DFC280 and software Leica application suite – LAS V4.

For mechanical tests a minimum of five tensile specimens were removed from each weld, transversely to the welding direction, and tested in a 10 (KN) universal testing machine, SHIMADZU AG-X, at room temperature, according to the ASTM: D638 standard. The samples were submitted to surface smoothing by milling in order to homogenise the thickness of the samples across the gauge section. The local strains were also determined by digital image correlation (DIC) using an Aramis 3D 5M optical system (GOM GmbH) and the procedure described in Leitão et al. [16]. Before testing, the specimens were prepared by applying a black speckle pattern randomly over the surface of the transverse samples previously painted mat white in order to enable data acquisition by DIC.

3. Results and discussion

3.1. Morphological and micrographic analyses

Visual analysis showed that almost all the welds made in this research displayed regular and smooth surface without porosity, as illustrated in Fig. 3 for a weld R1500T100F0.75. This result contradicts other studies where welded seams are full of voids, irregular or rough. The studies carried out by Scialpi et al. [17] resulted in non-flat welds where the welded seam grew out from the surface of the PP plates. The welds produced in PP composite with 30 (%) glass fibre by weight by Payganeh et al. [9] presented an extremely rough surface and in some cases they appeared to be irregular. Panneerselvam and Lenin [12] welded nylon 6 plates in which the produced welds presented a rough surface and pores in some cases.

The effect of tool rotational speed on the morphology of welds is illustrated in Figs. 4 and 5. As observed in Fig. 4 although all welds have a smooth surface, the crown formation at the weld depends on the rotational speed applied. The weld made with the lowest rotational speed (R1000T100F0.75) displayed many cavities on the retreating side (see arrow in Fig. 4(a)) suggesting that the heat generated on this side of the weld was not sufficient to promote bonding of material plastically deformed to the base material. With the increase of the rotational speed, the number of cavities decreased on the retreating side (see weld R1250T100F0.75 in Fig. 4(b)), and virtually disappeared on welds performed with 1500 (rpm), as illustrated in Fig. 4(c).

The defects present in the weld R1000T100F0.75 surface (Fig. 4(a)) extend along the entire thickness of the weld, on the retreating side, as can be seen in the micrograph of the cross section of this weld (Fig. 5(a)) which displays many cavities on the retreating side. In all micrographs the retreating side is located

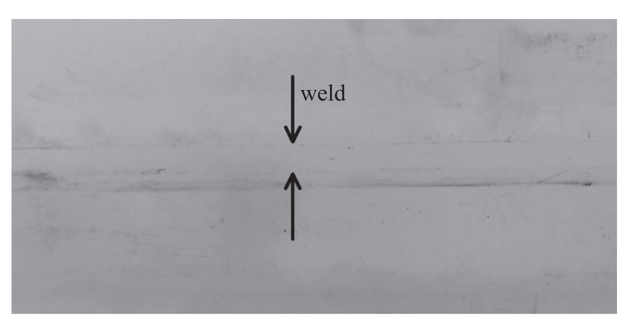

Fig. 3. Welded seam R1500T100F0.75.

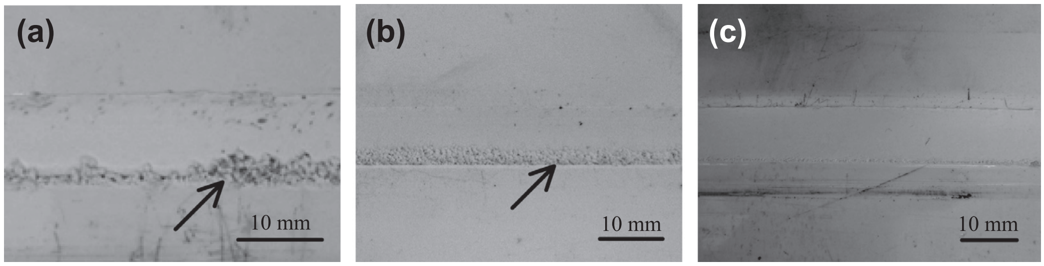

Fig. 4. Effect of rotational speed on the morphology of the weld crown: (a) R1000T100F0.75, (b) R1250T100F0.75 and (c) R1500T100F0.75.

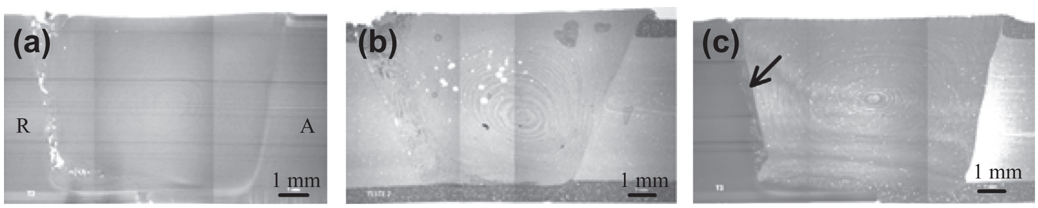

Fig. 5. Micrographs of welds performed with increasing rotational speed: (a) R1000T100F0.75, (b) R1250T100F0.75 and (c) R1500T100F0.75.

on the left, while the advancing side is on the right. This micrograph shows that the lack of bonding extends through the plate thickness. Bagheri et al. [18] have already observed that there was poor mixing of material in retreating side of FSW in ABS plates. This observation suggests that the heat generated on the retreating side is insufficient to establish bonding. This is explained by two factors:

- The heat generated on the advancing side is higher than on the retreating side, as mentioned by Aval et al. [19], who studied the effect of tool geometry on mechanical and microstructural behaviour of aluminium alloys.
- The poor thermal conductivity of ABS, which restricts heat conduction from the advancing to the retreating side.

In addition, the asymmetric flow of material in the stir zone should contribute to the formation of cavities on the retreating side. If the flow of material in the stir zone is similar to that observed in FSW of metals, the material pulled by the shoulder from the retreating to advancing sides is pushed downward within the pin diameter producing an onion ring-like structure, as mentioned by Leal et al. [20], similar to that shown in Fig. 5. However, as the temperature is lower on the retreating side, poor mixing of polymer dragged by the tool was obtained. Nandan et al. [21] show by FSW numerical simulation that in welding of mild steel material flow occurs mainly on the retreating side. The difference in material flow between advancing and retreating sides was also shown by Zhang et al. [22] using numerical simulation. Heutrier et al. [23] describe a dissymmetry between the advancing side and the retreating side of a FSW seam. According to these authors, this difference is due to the torsion and circumventing velocity fields which have different directions on the advancing and retreating sides. An element of material on the advancing side is more influenced by the vortex velocity field than an element of material on the retreating side. The vertical lines visible in the following micrographs are explained by the fact that each image is formed of several photos.

Fig. 5(b) shows that the increase of tool rotational speed to 1250 (rpm) decreased the number of cavities on the retreating side significantly, due perhaps to the increase in heat generated. However, it is still insufficient to promote complete bonding on this side. Furthermore, this image shows the presence of porosity in the nugget. This porosity is aligned with the lines of material flow and concentrated on the retreating side, suggesting that air can be trapped due to inadequate material flow. Oliveira et al. [24] suggest that voids observed in the friction spot welding of poly(methyl methacrylate) (PMMA) can be caused by thermal shrinkage, trapped air or even physicochemical structural changes such as structural water evolution.

With respect to the weld performed at the highest rotational speed (weld R1500T100F0.75), besides its excellent superficial quality, the surface is smooth and uniform and with a reduced porosity (Fig. 4(c)), as mentioned above. The micrograph shows good weld quality, without voids or porosity, and with a good mixture of material in the nugget zone, as illustrated in Fig. 5(c). However, a very narrow region of poorly mixed material can be observed on the retreating side, as shown by the arrow in Fig. 5(c). Therefore, it can be concluded that the increase in the tool rotational speed facilitates the flow and mixing of material, thus reducing the defects in the weld, although it proved insufficient in preventing poor mixing of material in a narrow zone on the retreating side.

The effect of the traverse speed on the weld crown appearance is illustrated in Fig. 6. Welds R1250T50F3.75 and R1250T100F2, made with the lowest traverse speeds, presented excellent superficial finishing, (Figs. 6a and b, respectively), unlike weld R1250T200F3.25, which presents a rough surface (Fig. 6(c)) likely caused by insufficient heat input. In fact, this weld has a ratio of rotational to traverse speeds (R (rpm)/T (mm/min)) of 6.25, while the previous welds show ratios equal to or greater than 10. This factor, as well as the excessive traverse speed, might prevent adequate heating of the shoulder. Nevertheless, no voids or porosity were observed on the surface of the welds. Thus, it can be stated that ratios of rotational/traverse speeds (R (rpm)/T (mm/min)) higher than 10 lead to good weld crown appearance. Weld R1250T100R2 was carried out between two ABS plates, one white and one black, in order to better illustrate the material flow lines. However, this procedure did not yield additional information on the micrographic analysis.

The micrographic images through the thickness direction showed onion ring-like structures in all welds, without regions of poor material mixing (Fig. 7). However, material flow vortices appear close to the root of the welds, when higher traverse speeds are applied (see Fig. 7b and c). Weld R1250T100F2 presents some porosity in the nugget, as does weld R1250T100F0.75, but unlike weld R1250T200F3.25, which was carried out with the same

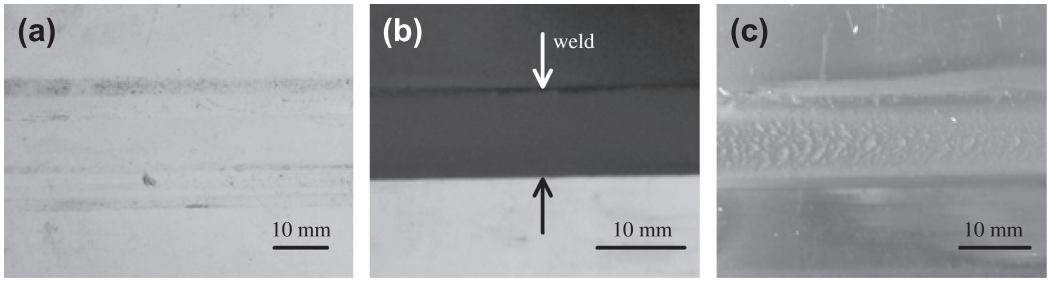

Fig. 6. Effect of traverse speed on the morphology of the weld crown: (a) R1250T50F3.75, (b) R1250T100F2 and (c) R1250T200F3.25.

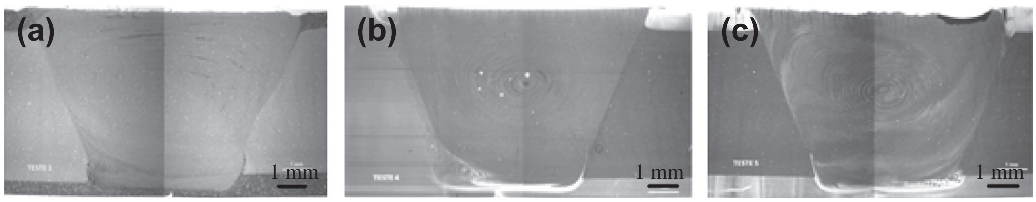

Fig. 7. Micrographs of welds performed with increasing traverse speed: (a) R1250T50F3.75, (b) R1250T100F2 and (c) R1250T200F3.25.

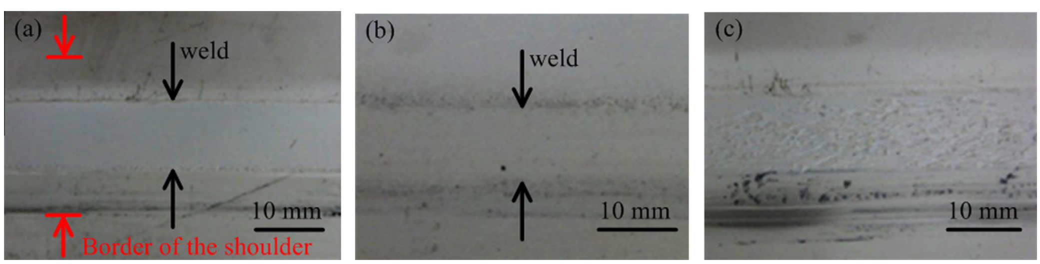

Fig. 8. Effect of axial force on the morphology of the weld crown: (a) R1500T100F0.75, (b) R1500T100F2.25 and (c) R1500T100F4.

rotational and higher traverse speed. This could be explained by the axial force applied in the latter weld, which is much greater than the force used in the weld R1250T100F2.

The effect of axial force on the quality of the weld was analysed based on welds carried out with constant rotational and traverse speeds (1500 (rpm) and 100 (mm/min) respectively), and variable axial forces of 0.75, 2.25 and 4 (KN). The crown appearance of these welds is shown in Fig. 8. The weld performed with the lowest axial force (R1500T100F0.75) displayed good superficial appearance, free of porosity on the crown surface, as shown in Fig. 8(a). The weld seam is uniform and does not present irregularities. The black line in the lower part of the image, which corresponds to the retreating side, was produced near the border of the stationary shoulder, probably due to the excessive heat generated during the process. An increase in axial load brought no substantial changes to the weld surface (see Fig. 8(b)), except for weld R1500T100F4 performed with 4 (KN), where a rough surface can be observed, as shown in Fig. 8(c). This rough surface can be explained by excessive friction between shoulder and polymer due to the high axial force for the heat input used.

The morphological observations through the thickness direction are showing that no cavities or pores formed in the stir zone of the welds (see Fig. 9). This proves that a minimum heat input is required to produce good welds, although weld R1500T100F0.75 (Fig. 9(a)) has a narrow zone of poorly mixed material on the retreating side (indicated by an arrow). This image is shown in Fig. 5(c), where the effect of tool rotational speed is evident. The combined analysis of Figs. 5 and 9 leads to the conclusion that in addition to a minimum threshold of rotational speed, i.e. a minimum amount of heat generated, a minimum axial force is also required in order to constrain the material in the stir zone, and prevent the formation of cavities, pores or zones of poorly mixed material. As in injection moulding of polymers, where a minimum threshold of pressure is needed to avoid shrinkage and porosity formation, in FSW of polymers a minimum threshold of axial force in needed to avoid the same defects and improve the mixing of material.

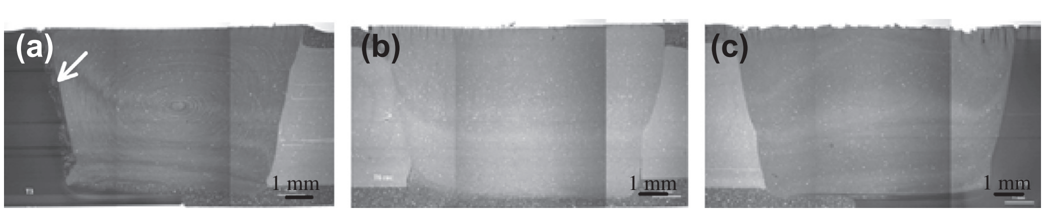

Fig. 9. Micrographs of welds performed with increasing axial force: (a) R1500T100F0.75, (b) R1500T100F2.25 and (c) R1500T100F4.

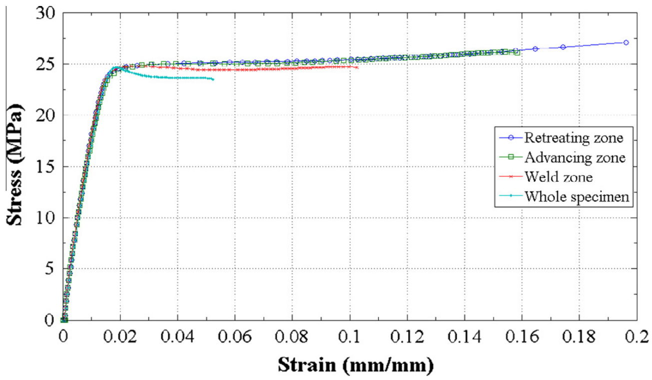

Fig. 10. Stress strain curve of the weld R1500T100F2.25.

3.2. Mechanical performance

Tensile testing was used to assess the effect of the welding parameters on mechanical properties (ultimate strength and strain at break) of the welds. Since DIC was used, the local deformation of the specimen can be considered. Fig. 10 shows a stress strain curve of the weld R1500T100F2.25 taking into account different zones of the specimen (retreating zone, advancing zone, weld zone, and whole specimen). All of these zones can be seen in detail in Fig. 12(b). In the data processing of these stress strain curves were considered mean values (strain and stress) for each zone. The retreating zone is the specimen region where maximum stain is reached. Consequently, the fracture of the sample initiates on the retreating side. The effect of tool rotational speed on stress and strain at break of welds is illustrated in Fig. 11. As this figure shows, tensile strength increases with increasing rotational speed, especially when 1500 (rpm) is applied. This result may be explained by the absent of voids on the retreating side and nugget zone of the sample (see Fig. 5). Therefore, when defects are present breakage is promoted as they work as stress concentration points. Thus, it can be concluded that the increase in rotational speed generates more heat, as stated by Strand [4], providing the proper flow of the polymer in the stir zone and preventing the formation of defects, thus increasing the strength of the welds. In general, the welds tested have a significantly lower tensile strength than the base material (Table 1), although the values obtained are similar to those of Bagheri et al. [18] in ABS welds obtained using a heated tool. This analysis complies with the work of Mostafapour and Azarsa [25] who point out that the increase in rotational speed leads to the local increase of material temperature in the joint line. Due to low thermal conduction of polymeric material, a large

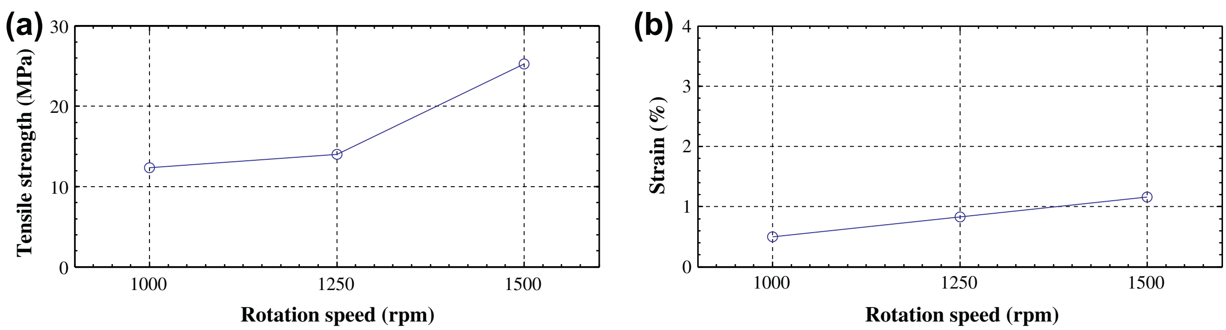

Fig. 11. Effect of tool rotational speed on: (a) tensile strength and (b) strain at break of welds.

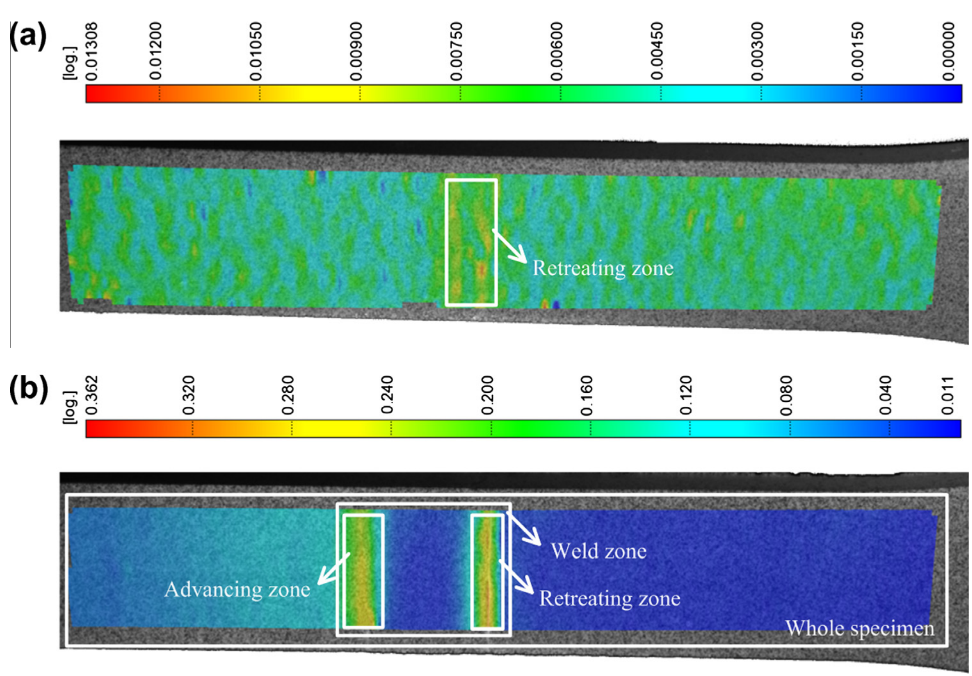

Fig. 12. Image of plastic strain of specimens: (a) R1000T100F0.75 and (b) R1500T100F2.25 just before break (Aramis image).

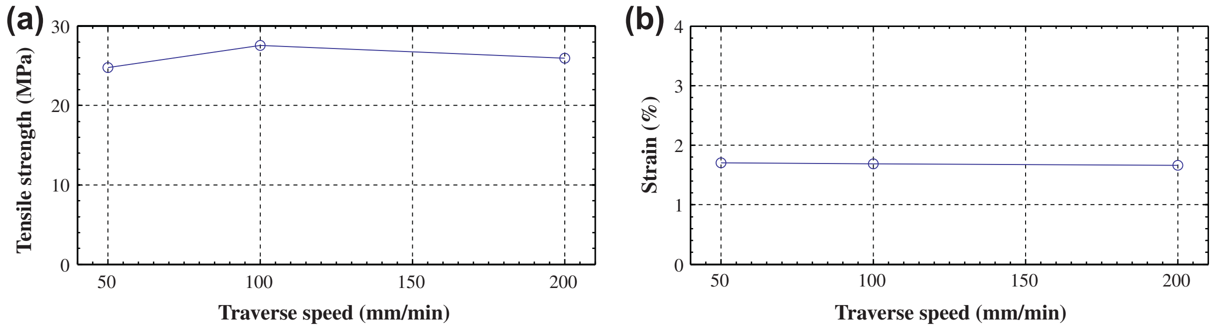

Fig. 13. Effect of tool traverse speed on: (a) tensile strength and (b) strain at break of welds.

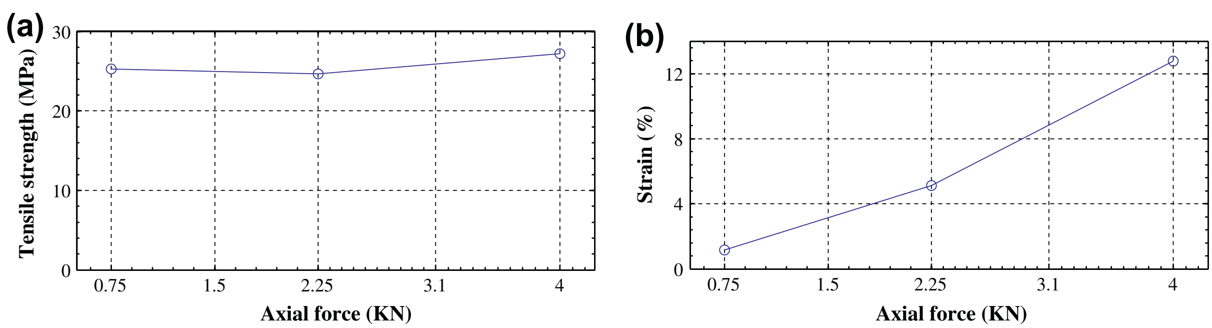

Fig. 14. Effect of tool axial force on: (a) tensile strength and (b) strain at break of welds.

amount of heat concentrates in the nugget zone. Consequently, the amount of molten material around the pin increases, and the stirring conditions are improved.

Fig. 11(b) shows that the increase in the tool rotational speed only generates a small increase in strain at break of the welds, despite being lower than the base material. This is because during the test plastic deformation concentrates at the transitions between the stir zone and the base material, mainly on the retreating side of the former where there is poor adhesion of the material, causing premature failure. Fig. 12 illustrates the actual strain field just before break on two tensile specimens removed from welds R1000T100F0.75 (Fig. 12(a)) and R1500T100F2.25 (Fig. 12(b)). The weld R1000T100F0.75 (Fig. 12(a)) has a specific zone on the retreating side with many cavities as shown in Fig. 5(a) and therefore the plastic deformation concentrates mainly on the retreating side of the weld, as shown by the yellow zone (see colour code above Fig. 12(a)). The weld R1500T100F2.25 (Fig. 12(b)) has no specific zone of poor mixing of material as shown in Fig. 9(b), and therefore the plastic deformation concentrates on both sides of the weld, as shown by the red and yellow zones (see colour code above Fig. 12(b)). The higher strain is reached in the retreating side as indicated in Fig. 10.

Regarding the influence of traverse speed on strength and strain at break of welds it is observed that there is no effect on the referred properties, at least for welds using high tool rotational speed (1250 (rpm)), as illustrated in Fig. 13. This can be explained by the poor thermal conductivity of the polymer which prevents the heat generated by the tool rotational from being transferred to the surrounding material. This is confirmed by the weld morphology that is similar in the different welds as shown in Fig. 7. Furthermore, these results comply with those of Sorensen et al. [26], who welded several polymeric materials (PP and HDPE) and concluded that traverse speed does not influence the weld quality. However, this results contradict recent results of Bagheri et al. [18], obtained on welds in ABS polymer. These authors report that the loss of strength of the welds with the increase in traverse speed is due to the poor mixing of the material caused by the reduction of the heat input from the heated shoe. In the present case no external heating system was used, and the heat was generated solely by tool rotation; no significant degradation of material mixing with increasing traverse speed could be observed, as shown in Fig. 7.

The effect of axial force on FSW of polymers has rarely been analysed in the literature because most of the welds are carried out in milling machines, where external force control devices are required. As previously mentioned, the axial force plays an important role in controlling the formation of defects in FSW of metals. In the present case axial force influences material mixture (Fig. 9), as well as the tensile plastic performance of welds, as shown in Fig. 14. Fig. 14(a) shows that the increase in axial force does not result in any tensile strength change. However, it is observed that is essential to improve the plastic strain performance of the weld, as illustrated in Fig. 14(b). In fact, welds performed with high tool rotational speed (1500 (rpm)) and high axial force (4 (kN)) have average strain at break values of approximately 12.8 (%) unlike most of the other welds, which fail to reach 2 (%). This is because the increase in axial force promotes better material mixing on the retreating side, providing welds without a zone of weak material mixture, as shown in Fig. 9.

Table 2
Tensile strength efficiency (%) and strain of welds (%).

W (RPM) → F (KN) ↓	1000		1250		1500	
	Strength efficiency (%)	Strain (%)	Strength efficiency (%)	Strain (%)	Strength efficiency (%)	Strain (%)
[0.75,1.5]	31	0.51	35	0.83	62	1.16
[1.5,3.0]	43	1.22	68	1.69	61	5.12
[3.0,4.0]	54	1.73	64	1.66	67	12.79

Nevertheless, all the specimens broke on the retreating side. This phenomenon has been studied by Bagheri et al. [18], who pointed out that material flow on advancing and retreating sides is quite different. Thus, lack of material on the retreating side can occur, which in turn increases brittleness in this zone.

The simultaneous effect of both tool rotational speed and axial force on the strength efficiency and strain of welds is shown in Table 2. The strength efficiency is the ratio between tensile strength of welds and base material. Table 2 shows that welds with strength efficiency rates above 60 (%) are reached when high tool rotational speed and axial force are used; furthermore, the axial force required to do welds with good quality decreases with increasing rotational speed. A similar effect is observed for strain, high strain performance is reached when high rotational speed and axial force are used. By the analysis of Table 2, it can be state that axial force is the most influent parameter to obtain high strain welds. Strain at break above 10 (%) is attained only in welds carried out with high tool rotational speed and axial force. The numbers between brackets in the left column of the Table 2 represent ranges of force.

The results of this study show that the strength of the weld is governed by the strength of the retreating side, which depends on the material flow in this zone. The adequate flow of material in this zone is only achieved for tool rotational speeds and axial forces above a certain threshold (rotational speed higher than 1250 (rpm) and axial force higher than 1.5 (KN)), when external heating is not used.

4. Conclusions

The aim of the present research is to study the effect of the tool rotational and traverse speeds, as well as the axial force, on the quality of welds carried out by friction stir welding on acrylonitrile butadiene styrene (ABS) plates, using a stationary shoulder tool without external heating. Based on the experimental results and discussion, the following conclusions can be drawn:

- It is feasible to produce good quality welds without any external heating.
- Tool rotational speed and axial force values above a certain threshold (rotational speed higher than 1250 (rpm) and axial force higher than 1.5 (KN)) are required to produce welds free of defects.
- Tool rotational speed generates the heat for plasticizing the polymer and promotes adequate material mixing.
- The axial force contributes to material mixing and prevents the formation of cavities in the retreating side of stir zone.
- The tensile strength and strain at break of welds is always below that of the base material.
- Welds of high strength efficiency and strain at break are achieved only when high rotational speed and high axial force are used.
- The main influence of traverse speed, when external heating is not used, is on the weld crown appearance. Good weld crown appearance is obtained when sufficient heat is provided to the welding joint. Thus, ratios of rotational / traverse speeds (R (rpm)/T (mm/min)) higher than 10 lead to good weld crown appearance.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.matdes.2014.02.036.

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