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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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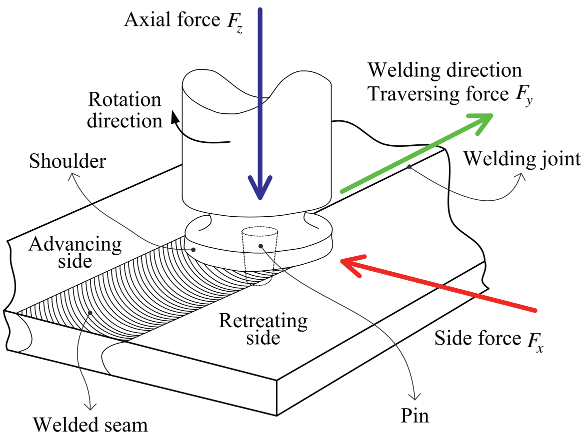

Fig. 1. Representation of the FSW process.

(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 $300 \times 80 \times 6$ (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) $\times$ 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