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Morphology and strength of acrylonitrile butadiene styrene welds performed by robotic friction stir welding

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ABSTRACT

The aim of this study is to examine the main factors affecting friction stir welding (FSW) of acrylonitrile butadiene styrene (ABS) plates, performed by a robotic system developed to this purpose. Welds were carried out using a tool with stationary shoulder and an external heating system. The welding parameters studied were the axial force, rotational and traverse speeds and temperature of the tool. The major novelty is to perform FSW of a polymer in a robotic system and to study the influence of the axial force on weld quality. In a robotic solution the control of axial force allows to eliminate robot positional errors and guarantee the contact between the FSW tool and the work pieces. Strength and strain properties of the welds are evaluated and correlated with the morphology of the welded zone. A comparison between welds produced in the robotic FSW system and in a dedicated FSW machine is presented. It is shown the feasibility of robotic FSW of ABS without deteriorating the mechanical properties of the welds in relation to those produced in the dedicated FSW machine.

1. Introduction

FSW of polymers is an attractive welding process due to the characteristics conferred to the welds. Strand [1] compared the most common welding processes used to join polymers, concluding that FSW is the process where it is achieved higher weld strength efficiency. This process enables the production of 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. The traditional FSW process is illustrated in Fig. 1. Nelson et al. [2] 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 [3], called hot shoe, which consists of a rotating pin and a static shoe heated by electrical resistances. This author 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 [4] succeeded in joining polypropylene (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. Scialpi et al. [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 weld crown 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 [8–12], to investigate the influence of some welding parameters in welded seams quality. The main drawback in the welded seams

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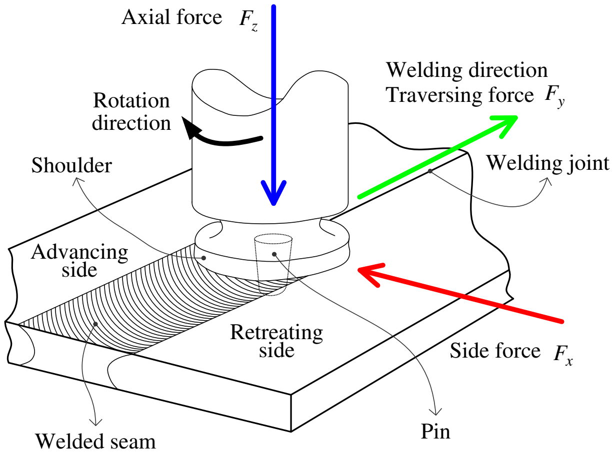

Fig. 1. Representation of the FSW process.

produced along these studies, as well as in the study carried out by Aydin [7], was bad surface quality of the welds. 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 that 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 welds. Arici and Sinmazçelýk [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 PP 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. [2]. 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, the best welds performed in PP and polyethylene terephthalate glycol (PETG) displayed about 90 (%) of tensile strength observed in the base material. 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. Bagheri et al. [15] have studied the influence of welding parameters rotational speed, traverse speed and shoulder temperature at the beginning of the FSW process. A hot shoe tool was used in this study and the good results allowed by this tool were observed once more. However, quality welds are only reported at low traverse speed values. A recent study proposed by Pirizadeh et al. [16] presented a new concept of FSW tool named self-reacting friction stir welding (SRFSW). This tool consists of two non-rotational opposing shoulders on the crown and root sides of the joint. It was studied the influence of the process parameters tool rotational speed, tool translational speed and shape of the pin. In spite of the fact that the authors have reported good results (high weld tensile strength), they are worse than the results presented by other studies [15,17]. This is likely because the design of the FSW tool that prevents the tool operates at high rotational speed and generates enough heat to promote a strong bond.

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. 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. Mendes et al. [17] proved that increasing the tool plunge axial force (*Fz* in Fig. 1) in FSW of ABS the weld defect size is reduced or removed and mechanical properties are improved. In fact, none of the previous studies use a robot to perform FSW of polymers and just Mendes et al. [17] present a preliminary study of the influence of axial force on the resultant welds. The use of anthropomorphic industrial robots in the FSW process can reduce the costs associated to this welding process and increase its flexibility. However, anthropomorphic industrial robots when submitted to high loads tend to present positional errors due to several factors:

- Low stiffness associated to its articulated structure.
- Vibrations due to robot structure and rotation of the tool.
- Positional error associated to the off-line programming process.

These kinds of difficulties are pointed out by Schneider et al. [18] and Leali et al. [19] in robotic machining, a manufacturing process that also requires high load capability. In this context, it is expected that the use of an industrial robot to perform FSW will require high load capabilities to produce quality welds. The majority of the published studies about FSW of polymers have been carried out in conventional milling machines that are robust machines and no positional or vibration difficulties arise.

In robotic welding systems, the axial force must be minimized due to the 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 authors did not find any study in literature making mention to the application of anthropomorphic robots with low bearing capacity performing FSW in polymers.

This paper studies the influence of welding parameters on the microstructure and mechanical properties of welds produced in a robotic system. The welding parameters analysed are axial force, rotational speed and traverse speed. Furthermore, the influence of tool temperature in weld crown appearance is also analysed. The presented welds were performed in a robotic system which may introduce some perturbations in the FSW process due to the reduced stiffness of the mechanical structure of an anthropomorphic robot when it operates with relatively high contact forces. Because of that, robotic welds were compared with welds performed in a conventional FSW machine [17], in order to analyse the influence on the weld quality of the robotic system developed.

2. Materials and methods

Square 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