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Technical Paper

Shoulder design developments for FSW lap joints of dissimilar polymers

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A B S T R A C T

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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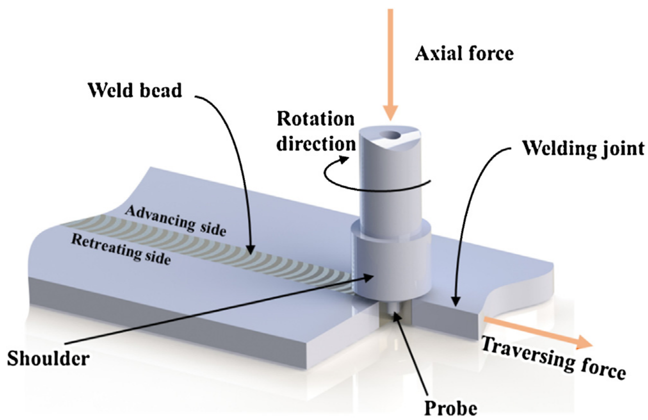

Fig. 1. FSW schematic representation.

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