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Friction spot welding of carbon fiber-reinforced polyamide 66 laminate

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Abstract: Friction spot welding (FSpW) is an innovative technique developed by the Helmholtz Zentrum Geesthacht (WO/2001/036144). FSpW uses the friction between a rotating tool and workpieces to generate enough heat to cause macromolecular interdiffusion across the interface of the joining partners to create the weld. In this work, the feasibility of FSpW on carbon fiber-reinforced polyamide 66 laminate (CF-PA66) was evaluated through lap shear testing and optical microscopy. CF-PA66 welds with good surface finishing, an absence of degradation flaws and an average lap-shear strength of 26.8 ± 0.8 MPa were achieved. These welds have comparable mechanical performance to state-of-the-art ultrasonic welds, which indicates the potential of the FSpW process for fiber-reinforced polymer composites.

Keywords: carbon fiber-reinforced composites, polymeric composites, welding, Friction Spot Welding

1. Introduction

The selection and development of lightweight materials, such as fiber-reinforced polymers (FRP), has largely increased in the last decades. Among the primary reasons for that are the new environmental policies for the reduction of greenhouse gas emissions. The inclusion of FRP in automotive structures has been used to design high-performance lightweight vehicles.

The state-of-the-art welding techniques for polymers (e.g. laser and ultrasonic welding) are consolidated technologies. However, their applications are restricted to certain types of polymers and geometries. The new friction-based welding processes have a number of advantages over other available joining techniques, including low power consumption, short welding times (2 to 20 s [5]), good weld mechanical performance and the absence of filler material [1]. Friction Spot Welding (FSpW) was developed and patented by the Helmholtz Zentrum Geesthacht (HZG) research center in Germany [2]. The technique was originally conceived to weld aluminum alloys [3], and, recently, it has been used to produce similar [4] and dissimilar [5] welds between thermoplastic polymers, fiber reinforced-composites and nanocomposites [6]. A variant of this process has been employed to join lightweight metal alloys with polymeric composites, in this case called Friction Spot Joining (FSpJ) [7].

The FSpW technique of thermoplastic polymers uses friction between a non-consumable tool and the welding parts to heat and locally soften or melt the polymer and create a weld by macromolecular interdiffusion. One major advantage of FSpW is that the material refilling of the spot weld volume avoids the generation of a keyhole, an undesired feature usually found in similar processes, such as Friction Stir Spot Welding [8]. The absence of a keyhole usually increases the joint strength by producing a larger welded area and decreasing the stress concentration associated with the hole's notch effect.

The FSpW tool used consists of three different coaxial pieces made of nitrided TiAl6V4 titanium alloy (Fig. 1-a), with geometry reported in [6]. TiAl6V4 alloy, a high-strength alloy with lower thermal conductivity, was selected to reduce heat losses to the welding head. The clamping ring is used to keep the welding pieces together on a backing bar. The pin and the sleeve are responsible for creating frictional heat with the workpieces through rotation and axial pressure.

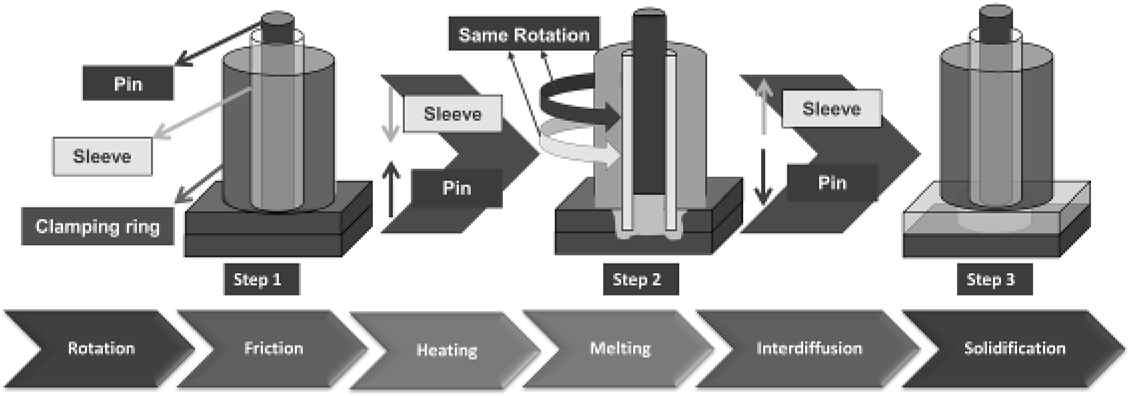

Fig. 1. Illustration of the FSpW process, showing the tool and the main steps

The FSpW process is divided into three main phases (Fig. 1). In the first step, the specimens are overlapped and fixed against a backing bar by the clamping ring under a constant joining pressure (JP). In the second step, the pin and the sleeve start to rotate in the same direction at a preset rotational speed (RS) during a given friction time (FT). The sleeve plunges the specimens, and the friction between the tool and workpieces generates enough heat to locally soften or melt the polymer. Simultaneously, the pin retracts, creating a gap that is filled by the softened polymer. After the plunge depth (PD) is reached, the third step begins when the sleeve and the pin return to their original position and the softened polymer entrapped in the formed gap is pushed back by the pin, refilling the void left by the sleeve. By the end of the welding cycle, the tool can be either retracted or kept in contact with the welding pieces to allow the joint to cool down under pressure to decrease thermal shrinkage and avoid defects; this parameter is called the holding pressure time (HPT).

In this work, the feasibility of FSpW on carbon fiber-reinforced polyamide 66 laminate (CF-PA66) was investigated through mechanical testing and optical microscopy. To our knowledge, this study reports for the first time the friction spot welding of woven reinforced thermoplastic composites.

2. Materials and Methods

A 2-mm-thick carbon fiber-reinforced polyamide 66 laminate (TEPEX-201_C200(2)_C190(7), Bond Laminates, 49 vol.% fibers, 2/2 twill configuration with 2 plies of C200 and 7 plies of C190, tensile strength of 580 MPa , in-plane shear strength of 114 MPa) , was machined to produce 100 x 25 x 2 mm^3 welding specimens.

Single lap joints were produced in an RPS 100 friction spot welding equipment (Harms & Wende, Germany) within the following parameter ranges: JP of 5-12 kN, RS of 1000-3000 rpm, PD of 1.8-2.2 mm, FT of 3.6-7.5 s and HPT of 0-20 s.

The surface temperature of the specimens was monitored using an infrared camera in the range of 0 to 300ºC with 30 Hz data acquisition rate during 180 s. Measurements were performed immediately after tool retraction by the end of the welding process. Microstructure was evaluated by reflective light optical microscopy. Mechanical performance was evaluated by single lap shear testing in accordance with ASTM D3163 [9] at room temperature and a crosshead speed of 1.27 mm min^{-1}.

3. Results and Discussion

Fig. 2 (a) and (b) show, respectively, the typical cross-sectional and longitudinal views of a defect-free CF-PA66 weld produced by FSpW under the following processing conditions: JP of 5 kN, RS of 3000 rpm, PD of 2.0 mm, FT of 7.5 s and HPT of 20 s (ongoing investigations indicated that HPT can be cut off by less than half of the time used in this work). The interface between the upper and lower plates can be seen in Fig. 2a, while the boundaries between the stir zone (SZ) and the thermo-mechanically affected zone (TMAZ) can be seen in both Fig. 2a and Fig. 2b. The material around the sleeve is affected mechanically by the rotating motion and thermally by the heat generated during the friction. The stirring and plunging actions of the sleeve melt the polymer and break the woven carbon plies in the sleeve path. This region is called the stir zone (SZ), and it exhibits a mixture of polymer and broken carbon fibers orientated in the direction of the sleeve rotation. The material beyond the border of the stir zone is called the thermo-mechanically affected zone (TMAZ). Unlike the SZ, which has direct contact with the tool, the TMAZ is thermally affected by heat conduction and mechanically affected indirectly by the material flowed from the SZ.

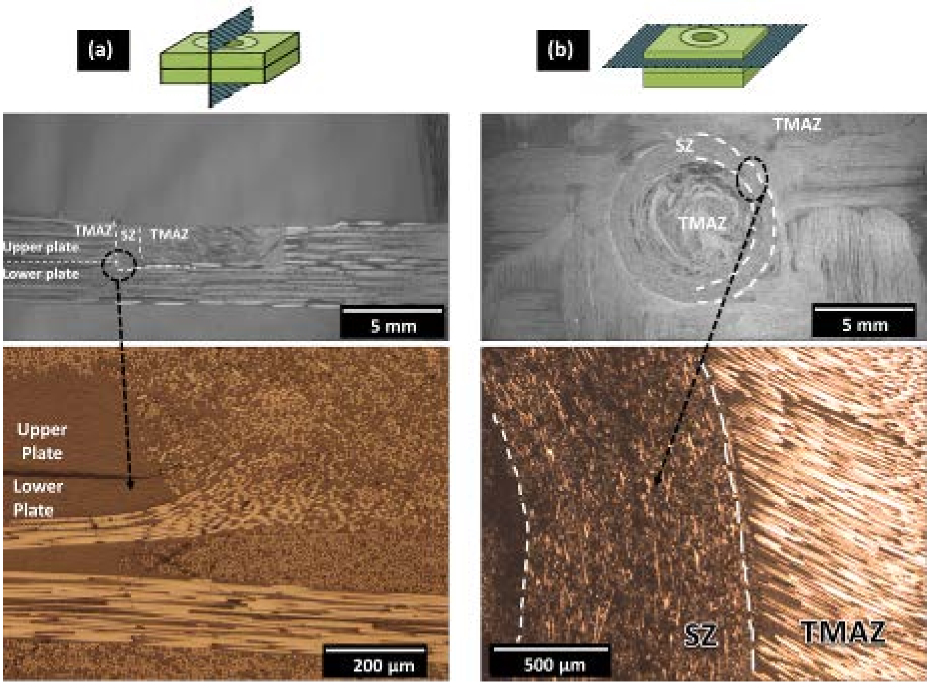

Fig. 2. Microstructure of a CF-PA66 weld produced by FSpW. The interface between the upper and lower specimens is shown in the mid cross-section view (a), and the boundaries between the stir zone (SZ) and the thermo-mechanically affected zone (TMAZ) are shown in both cross-section (a) and longitudinal (b) views.

Fig. 3 shows the surface finishing, microstructure (cross-section views) and temperature distribution after the tool retraction for two CF-PA66 welds produced by FSpW without (Fig. 3 (a)) and with a holding pressure time (HPT) of 20 s (Fig. 3 (b)), keeping the other process parameters constant. In the case without HPT, the average weld surface temperature at the end of the process was slightly higher (266ºC) than the melting point of the PA66 (260ºC). In this case, a poor surface finishing with flaws, such as voids, was created because of the low viscosity of the material and differential contraction during the cooling. In the case with HPT, the average weld surface temperature was 103ºC, which is reasonably below the PA66 crystallization point (235ºC), and, hence, the welded material in the center of the weld had enough time to cool down under pressure, leading to an improved welded area without voids and with good surface finishing as a result of lower polymer shrinkage.

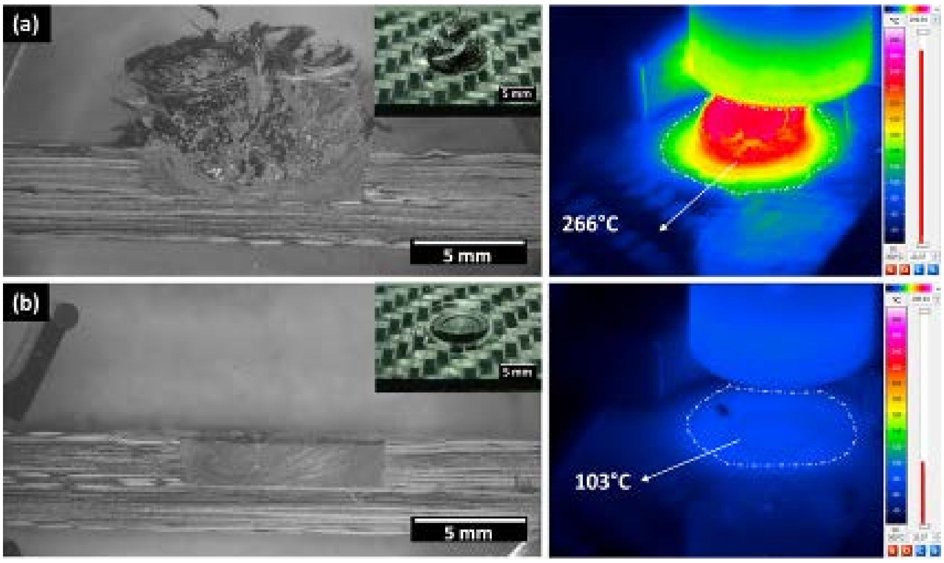

Fig. 3. Surface finishing, microstructure (cross-section view) and temperature profile of two CF-PA66 welds produced by FSpW without (a) and with an HPT of 20 s (b). The other welding parameters were kept constant: JP = 5 kN, RS = 3000 rpm, PD = 2.0 mm and FT = 7.5 s

Fig. 4 (a) shows the force-displacement curve for a set of three replicates of CF-PA66 welds produced by FSpW at JP = 12 kN, RS = 3000 rpm, PD = 2.0 mm, FT = 7.5 s and HPT = 20 s. At this condition, the average joint lap-shear strength was 26.8 ± 0.8 MPa. The lap shear strength of FSp welds was obtained from a nominal area of 63.6 mm^2 calculated from the external sleeve diameter of 9 mm ($A_0 = \pi \cdot Radius^2$). Liu *et al.* [10] obtained comparable ultimate lap shear strength of 19.4 MPa (specimens with nominal welded area of 25.4 x 12.7 mm^2) using ultrasonic welding in a similar carbon fiber-reinforced polyamide ([0]$_{16}$ stacking sequence and 53% fiber volume). All tested specimens exhibited the "interfacial shear failure" fracture mechanism (Fig. 4-b) similarly to reference [10].

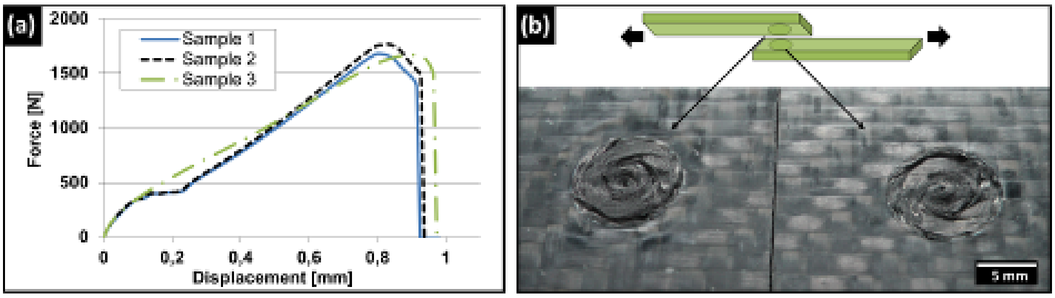

Fig. 4. (a) Force-displacement curve in the lap-shear test for a set of CF-PA66 welds produced by FSpW . (b) Interfacial shear failure fracture mechanism.

4. Conclusions

The feasibility of FSpW on CF-PA66 was successfully demonstrated. CF-PA66 welds with good surface finishing, the absence of volumetric defects and a lap-shear strength up to 26.8 MPa were achieved. Although in their early stage of development, these welds showed comparable mechanical performance to similar joints produced with state-of-the-art welding technology reported in the literature. This is an indication of the potential of the FSpW process for woven reinforced polymer composites.

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