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Strength development versus process data in ultrasonic welding of thermoplastic composites with flat energy directors and its application to the definition of optimum processing parameters

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ABSTRACT

Ultrasonic welding of thermoplastic composites is a very interesting joining technique as a result of good quality joints, very short welding times and the fact that no foreign material, e.g. a metal mesh, is required at the welding interface in any case. This paper describes one further advantage, the ability to relate weld strength to the welding process data, namely dissipated power and displacement of the sonotrode, in ultrasonic welding of thermoplastic composite parts with flat energy directors. This relationship, combined with displacement-controlled welding, allows for fast definition of optimum welding parameters which consistently result in high-strength welded joints.

1. Introduction

Ultrasonic welding is a very attractive assembling technique for thermoplastic composites since it is very fast, it does not require the use of foreign materials, e.g. a metal mesh, at the welding interface regardless the nature of the material being welded and it provides excellent quality joints. It is very well suited for the welding of small areas and it can, in principle, be applied in a sequential manner for the welding of larger areas [1]. The main points of attention for ultrasonic welding are that specific joint designs are generally needed to concentrate the ultrasonic energy at the welding interface, the welding parameters are highly coupled and it shows high sensitivity to tolerances and clamping of the parts to be welded. Ultrasonic welding of unreinforced thermoplastic parts is an assembly process widely used in the plastics industry [2]. As for its application to fibre-reinforced thermoplastic composites, ultrasonic welding is common practice for stacking the individual pre-preg layers during hand lay-up, of which a step beyond is automated fibre placement based on ultrasonic heating [3–5]. However, unlike other techniques such as resistance or induction welding [6,7], ultrasonic welding has not been industrially applied to the structural joining of thermoplastic composite parts. The development of robust welding procedures based on the understanding of the process is deemed as a necessary step to increase the readiness level of this technology, which, owing to the very short welding times, could be a very cost-effective solution for the assembly of mass-produced parts such as clips and brackets in composite aircrafts or composite automotive parts.

The ultrasonic welding process mainly consists of a vibration phase followed by a solidification phase. Ultrasonic heat is generated during the vibration phase of the process upon the application of pressure and of high-frequency (10–70 kHz) and low-amplitude (10–250 μm) vibrations transverse to the parts to be welded [2]. The main heating mechanisms are surface friction and viscoelastic friction [8,9]. During the solidification phase, the weld is allowed to cool down under pressure below the glass transition temperature T_g of the thermoplastic resin to achieve consolidation. The main process parameters are:

(i) Welding force, amplitude of vibration and vibration time, for the vibration phase.
(ii) Solidification force and solidification time, for the solidification phase.

Mechanical vibration and welding and solidification forces are applied to the parts to be joined by means of a sonotrode. The sonotrode is connected to a piezoelectric transducer through a booster. The piezoelectric transducer generates mechanical vibration, which is amplified by the booster and the sonotrode. The support collar of the transducer–booster–sonotrode system is attached to a pneumatic press that provides vertical movement along with the welding and the solidification force.

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Energy directors are used in ultrasonic welding to promote heat generation at the interface between the parts to be joined. Energy directors are traditionally man-made resin protrusions on the welding surfaces. As a result of their smaller cross section, they undergo higher strains during the welding process and hence experience higher viscoelastic heating rates than the bulk material [10]. Unreinforced thermoplastic parts intended to be assembled through ultrasonic welding are directly moulded with energy directors on the joining surfaces. In the case of ultrasonic welding of thermoplastic composite parts, energy directors made of the matrix resin have been traditionally moulded on the already consolidated adherends in a secondary production step [11–14]. Based on regular procedures of the plastics industry, these energy directors are usually linear ridges with triangular, rectangular or semicircular cross sections [15]. The shape, size, number and orientation of the energy directors have a major effect on the welding process and its results, since they influence heat generation and resin flow at the welding interface [14,16–18]. Quite recently Villegas has presented in [19] successful results obtained with flat energy directors consisting of a loose matrix resin film placed at the welding interface (Fig. 1(a)). Preferential heating of the flat energy director occurs as a result of the lower compressive stiffness of the neat resin film as compared to the stiffness of the composite adherends. The use of flat energy directors greatly simplifies ultrasonic welding of thermoplastic composites and provides 100% welded areas without the need for extensive optimisation of the interfaces, i.e. the definition of optimum shape, size, number and position of the energy directors.

Apart from its high assembly rates, a significant advantage of ultrasonic welding of thermoplastic composites as compared to other welding techniques is that it allows for in situ monitoring through process data. This possibility was first indicated by Benatar and Gutowski in [11], who analysed changes in the dissipated power and the acceleration of the base caused by the flow of triangular energy directors. Villegas built on this idea and showed in [19] a clear correlation between the feedback of a microprocessor-controlled welder and the physical changes at the welding interface for flat-energy-director ultrasonic welding. In that study the dissipated power and the displacement of the sonotrode were found to define five distinct stages within the vibration phase of the welding process as shown in Fig. 1(b) and described in what follows.

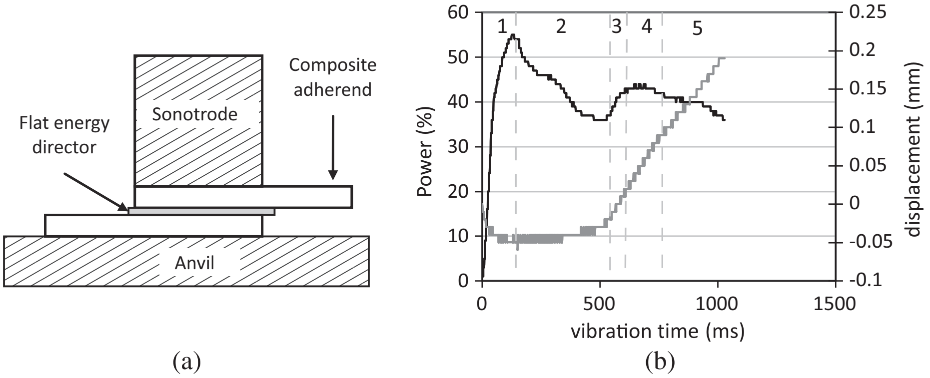
- *Stage 1*: heating of the energy director without any observable physical changes at the welding interface. This stage features a continuous increase of the dissipated power until a maximum is reached.
- *Stage 2*: the flat energy director starts to locally melt as a hot-spot nucleation and growth process. Surface friction heating mostly controls the nucleation of hot spots and, as described in [9], it triggers the viscoelastic heating mechanism, which has a predominant influence in the growth of hot spots. Stage 2 is characterised by a power decrease while the displacement of the sonotrode stays constant.
- *Stage 3*: the whole energy director is molten. This stage is characterised by a simultaneous increase of the power and by downward movement of the sonotrode (increased displacement in Fig. 1(b)), which pushes the uppermost adherend downwards and causes squeeze flow of the molten energy director.
- *Stage 4*: along with the flow of the energy director, the matrix in the uppermost layers of the composite adherends starts to locally melt. This stage features a plateau in the dissipated power.
- *Stage 5*: melting of the matrix in the adherends is predominant in this stage, which is characterised by a drop in the power.

This paper goes one step beyond by investigating the applicability of the process data provided by the welder to simplifying the definition of optimum process parameters in ultrasonic welding of thermoplastic composites with flat energy directors. Optimum sets of process parameters, i.e. those that result in high-strength welds, are usually defined for other welding techniques by correlating the temperature at the welding interface and the pressure with the weld strength. This correlation usually involves extensive experimental work and/or the development of heat transfer and consolidation models [20]. In the specific case of ultrasonic welding there is an added complexity that derives from the difficulty of measuring temperatures at the welding interface. If thermocouples are placed between the adherends they tend to act as energy directors and therefore they significantly alter the process. The use of alternatives such as infrared thermography is limited due to restricted access to the welding area, which remains covered by the sonotrode during the entire process. This work has a twofold aim: firstly, defining relationships between the weld strength and the power and displacement data provided by the ultrasonic welder; secondly, establishing a procedure that allows using such relation as a tool to consistently obtain high-strength welds. A purely experimental approach is followed based on mechanical testing, fractography and cross-sectional analysis.

2. Experimental

2.1. Adherends

The material used in this study was Cetex® CF/PEI (carbon-fibre reinforced polyetherimide) with 5 harness satin fabric reinforcement,



(a) (b)

Fig. 1. (a) Schematic of the ultrasonic welding process with flat energy director (dimensions not to scale). (b) Five stages in the vibration phase of ultrasonic welding as defined by the dissipated power (black) and displacement of the sonotrode (grey) curves (CF/PEI, 300 N, 82.6 μm, 0.25 mm-thick flat energy director). The power is represented as a percentage of the maximum available power (3000 W). Positive displacement represents downward movement of the sonotrode.