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Experimental assessment of the influence of welding process parameters on Lamb wave transmission across ultrasonically welded thermoplastic composite joints

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ABSTRACT

One of the advantages of thermoplastic composites relative to their thermoset counterparts is the possibility of assembling components through welding. Ultrasonic welding in particular is very promising for industrialization. However, uncertainty in the fatigue and fracture behaviour of composites is still an obstacle to the full utilisation of these materials. Health monitoring is then of vital importance, and Lamb wave techniques have been widely recognised as some of the most promising approaches for that end. This paper presents the first experimental study about the influence of welding travel on the transmission of Lamb waves across ultrasonically welded thermoplastic composite joints in single-lap configuration. The main aim of this research is to start to understand how guided waves interact with the internal structure of ultrasonic welds, so that benign, manufacturing-related structural features can be distinguished from damaging ones in signal interpretation. The power transmission coefficient and the correlation coefficient proved to be suitable for analysing the wave propagation phenomena, allowing quantitative identification of small variations of weld-line thickness and intermolecular diffusion at the weld interface. The conclusions are used to develop a tentative damage detection criterion which can later on assist the design of a Lamb wave based structural health monitoring system for thermoplastic composite structures. The Lamb wave test results are backed up by phased-array inspections, which also provide some extra insight on the internal structure of ultrasonic welds.

1. Introduction

Ultrasonic welding is a very promising technique for joining thermoplastic composite (TpC) components in aircraft primary structures [1–3]. From a mechanical point of view, it allows joints to have high static properties, low through-thickness porosity and lower weight when compared to their fastened counterparts. From a production point of view, the technique has a high potential for industrialisation not only due to short welding times of small joining areas, but also due to the possibility of reliably controlling the process. Villegas [2,3] and Villegas et al. [1] have demonstrated that it is possible to adopt a simple ultrasonic welding setup with flat energy directors (EDs) and use the displacement and power curves from

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the sonotrode to monitor the entire process and define the quality of the weld. By stopping the welding process at the maximum power plateau/point, it is possible to maximise lap shear strength for a certain "*material and welding set-up*" combination [2], with the travel at that point consistently corresponding to between 40% and 60% of the thickness of the flat ED. Consistent weld quality can hence be obtained when the welding process is controlled by the displacement of the sonotrode, referred to as welding travel. The cross-section of the optimised ultrasonically welded (USW) TpC joints is characterised by a very thin ($\sim 10^{-2}$ mm) polymeric weld-line between the adherends (consisting of the ED which was not squeezed out of the overlap), and a region within the two laminate layers, adjacent to the weld-line, which is affected by partial fusion of the matrix during the welding process and which extension is determined by the applied force and vibration amplitude [2,3]. Although this heat-affected zone does not have a separation surface as the weld-line, it is expected to have different elastic properties from the rest of laminate. Villegas [2] showed that different welding travel values directly result in different weld-line thicknesses. However, when welds produced with different travels are tested for lap shear strength, different features are observed on the fracture surface. This seems to indicate that travel also affects the effectiveness of intermolecular diffusion between the resin-rich weld-line and the adherends, which is attributed to different times available for heat to be transferred from the ED to the composite substrates.

The introduction of new composite structures in civil aviation has been driving the change towards condition-based maintenance (CBM) as an alternative to the regular inspection interval approach [4]. In turn, CBM has been pushing forward the development of structural health monitoring (SHM) technology capable of reliably assessing the structural integrity of a component during flight or at pre-flight checks. Among all of them, Lamb wave techniques are widely recognised as some of the most promising approaches for SHM of composite structures [5]. In previous work, the authors have investigated barely visible impact damage at multiple locations using Lamb wave techniques [6].

Accurate quantitative diagnostics can only be performed if ultrasonic response changes can be unambiguously correlated to specific damages. That correlation requires the distinction of benign features from damaging ones. Therefore, before designing any SHM system for a component it is first necessary to understand the influence of several intrinsic characteristics of the undamaged joints on Lamb wave propagation.

Most of the research about this problem has been focused on the interaction of Lamb waves with adhesively bonded metallic joints. Rokhlin [7] used theoretical and experimental analysis to show two important facts. First, that multilayer Lamb-type modes can carry ultrasonic energy across an overlap if their mode shapes match well enough with those of the modes in the adherends (which in mathematical terms is measured by the degree of orthogonality between the mode shapes in the two domains [8]). Second, that the sensitivity of Lamb modes to the bond properties depends on the sensitivity of their carrier modes to the same properties. In turn, that sensitivity is determined by the modes shapes in the overlap, which also vary with joint shape. Rokhlin pointed out that if bond inspection is to be performed, then the excitation Lamb mode should be selected such that it is allowed to convert (to some extent) to the necessary carrier modes.

Lowe et al. [9] went deeper into the physics of transmission across lap joints by investigating the mechanism that governs mode conversion at the edges of the overlap. By using finite element analysis and the two-dimensional fast Fourier transform (FFT), they proved that if there are multiple carrier modes, the strength of transmission of the zero-order single-plate symmetric (s0) Lamb mode is determined by their interference when mode conversion occurs at the trailing edge of the overlap. That interference can be mainly constructive or destructive, depending on the relative phases of the carrier modes. The longer the bond and the higher the wavenumber of the carrier modes (which is a function of bond thickness), the larger the phase change during propagation through the overlap, the more constructive the interference, and therefore the stronger the transmission. Therefore, by measuring the transmission coefficient of a certain Lamb mode, it may be possible to detect anomalies in the modal properties of the carrier modes caused by defects in the joint. Later, Lanza di Scalea et al. [10] adopted a fully experimental approach based on air-coupled piezoelectric transducers to study the strength of transmission of the a0 Lamb mode across adhesively bonded aluminium-epoxy-aluminium joints. Not only they were able to confirm the aforementioned carrier mode principles by measuring intermediate (adherend-overlap) transmission coefficients, they were also able to distinguish different bond conditions by measuring overall (adherend-overlap-adherend) transmission coefficients. Additionally, interesting conclusions were drawn about the most adequate frequencies for bond monitoring, with different frequencies being sensitive to different bond states.

With the research by Matt et al. [11] the problem of Lamb wave based SHM of fully composite joints was finally addressed by studying the transmission of the s0 mode across adhesive bonds. The test case was a carbon-epoxy wing skin-to-spar configuration containing areas of different bond condition, namely properly-cured, poorly-cured and disbonded. The specimens were instrumented with permanently attached inter-digital transducers which were used to acquire overall energy transmission coefficients. Changes in ultrasonic strength of transmission allowed three different bond states to be discriminated, although the most sensitive frequency range (100–300 kHz) was considerably lower than the one found in [10] (580–670 kHz) for adhesively bonded metallic joints.

However, TpC joints produced by ultrasonic welding have a unique structure, which properties are considerably different from adhesive bonds and are still not fully understood [12]. Not only the bonding nature is different (intermolecular diffusion [13] instead of adhesion), with unclear influence on the continuity of strain and stress across the overlap, but also the range of bond thicknesses is ten times smaller than in the case of adhesively bonded joints. Consequently, the interactions experienced by guided waves in USW joints fall outside the domain of understanding obtained from previous research.

Therefore the purpose of this paper is to investigate the influence of the welding travel on the transmission of Lamb waves across USW TpC lap shear joints, thereby serving as the first step towards understanding the propagation of guided