AIR-COUPLED ULTRASONIC LAMB WAVES FOR PROCESS MONITORING

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Introduction

Sandwich structures consisting of a foam core and metal or composite skins find widespread use because they combine structural strength with good thermal insulation at a light weight. Aerospace carbon components are usually produced using pre-made blocks of foam as core with the epoxy matrix functioning as glue between core and skins. The key requirement for steel-foam sandwich elements (SFSE) is a cost-effective production process which leads to a polyurethane (PUR) core foamed in-situ between two steel sheet skins. The PUR supplies the core as well as the glue for bonding to the skins. The chemical and physical processes (foaming and polymerisation) at the steel surface are critical for the quality of the final element - poor adhesion will lead to delaminations under thermal load (day-night-cycle) and costly replacement of the panel. While there are established methods to study the dynamics of a free foam ("Foamat", [1]) and the chemical reactions (e.g. FTIR-spectroscopy, [2]), currently none is capable to monitor the processes at the boundary to the "natural" substrate of the foam, the steel sheet. We present a new approach to probe the behaviour of the reactive mixture and its transition to a fluid and later solid foam, by using an air-coupled ultrasonic plate wave ("Lamb wave") in the substrate. The methodology is introduced along with a case study of its application for monitoring of a similar process of coating drying (fluids, paint) on a steel substrate.

Methodology

The selective excitation of plate waves by air-coupled ultrasound (ACU) in the slanted mode is the basis of all experiments. The incident angle of the ACU beam can be adjusted until its pressure distribution on the plate surface matches the wavelength of the lowest order anti-symmetric (a_o) plate wave. After a propagation distance of a few centimetres the plate wave is detected by a second transducer; the waveform is digitized and stored. A discrete Fourier transform (DFT) recovers the amplitude and phase of the output signal, even if it is very week. A similar setup has previously been used for non-destructive testing [3] and precise measurement of plate and surface wave velocities [4]. In the thin-plate limit, the phase velocity of the a_o-mode of a plate wave can be approximated as [5]:

$$v_{a_o} = \sqrt[4]{\frac{E}{3\rho(1-\nu^2)}}\sqrt{\frac{\omega D}{2}}\,. \tag{1}$$

It is determined by the Young's Modulus E, mass density ρ, Poisson's number ν, the circular frequency $\omega = 2\pi f$ and the plate thickness D. Any perturbations in the mechanical state of the substrate (thin coatings) can be considered by contributions to the stiffness, mass density or thickness thereby changing them to effective values. For example a thin fluid layer will contribute to the mass, while no change to the bending modulus of the plate is expected, thus reducing the plate wave velocity. Changes in the velocity are detected by tracking the phase of the received ultrasonic signal.

To simulate an industrial-style production of SFSE in the lab, a compact (100x100x80 cm) foaming cell for manufacturing test specimens (adhesive strength, based on DIN 53292) was constructed. Acquisition of the ultrasonic signal is always started on the undisturbed substrate before adding the reactive mix of polyol and isocyanate which will produce the foam.

Basic Results and Discussion

Figure 1 shows the phase variation of the plate wave during foaming. When the liquid reactive mixture first hits the plate, the phase exhibits a negative shift (lower wave velocity). As the PUR forms a liquid foam that has neither significant density nor stiffness, the phase recovers and then, as the foam hardens, reaches a plateau above the initial value (higher velocity due to stiffening). Destructive testing of the produced sandwich elements is currently being implemented at the LFK to estimate the correlation with the ACU-measurements.

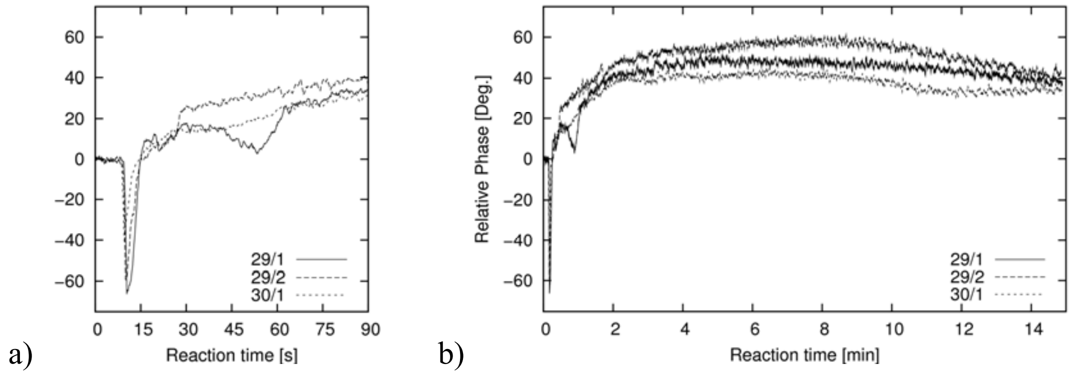

Figure 1: Phase variation of the plate wave during foaming: start (a) and full time scale of the reaction (b).

Summary

ACU with plate wave mode conversion has been shown to provide a remote, non-contact non-destructive means for monitoring reaction processes on plate-like substrates.

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