



Lamb waves characterization of adhesion levels in aluminum/epoxy bi-layers with different cohesive and adhesive properties



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ABSTRACT

This paper presents a study of the detectability of the level of adhesion at the Aluminum/Epoxy interface using the propagation of ultrasonic guided waves. The topic is relevant to the long-range ultrasonic inspection of structural adhesive bonding. The samples considered are epoxy-coated aluminum: samples were fabricated with partially or totally crosslinked epoxy groups and with different surface treatments of aluminum substrates. Experimentally measured dispersion curves and attenuation coefficients of a selected mode are used to quantitatively track changes at the epoxy-aluminum interface. The results show that modes could be very sensitive to the nature of the interface, that is to say to the level of adhesion, if properly selected. Numerical predictions via the Jones rheological model and their comparison with experimental results highlight three adhesion levels: weak, medium and high one.

1. Introduction

Adhesive structural bonding is an attractive and promising technology due to the potential advantages of lightness and distribution of stresses over the entire bonded surface. It allows bonding metal/metal, metal/composite material or composite material/composite material, which are new challenges [1,2]. However, it is in only emerging in industrial sectors such as the aeronautic or the automobile; indeed the development of this technique is still hindered by the fact that there is no nondestructive method using ultrasounds for certifying the mechanical quality of an adhesive bond. Therefore, there is the necessity of developing control and evaluation methods that can assess the quality of the adhesion of the bonded structure, the estimation of its aging, and the appearance of any damage that could deteriorate the quality of the bonding and its strength. Ultrasonic nondestructive methods are widely applied, particularly in the aircraft industry to test different sensitive parts of a plane. Bulk waves as well as guided Lamb or shear horizontal (SH) waves are used and different approaches to extract information about the bonding quality are developed, as can be found in references [3–8] such as non-exhaustive examples. The evaluation given by these methods is strongly correlated to the cohesive and

adhesive aspects, and the process adopted for the manufacturing of the bonding. Indeed, one has to make bonding specimens of reproducible and controlled properties, to make credible any association of the obtained measures to the actual quality of the bonding, as highly recommended by the US Federal Aviation Administration. That's why this work is collaboration between physico-chemists for the samples realization, and acousticians for ultrasounds characterization. The aim is to evaluate and discriminate different levels of adhesion in a bilayer structure, made of an aluminum substrate coated with an epoxy layer, using guided ultrasonic Lamb waves. These waves are found to be efficient tools to characterize adhesive bond properties [9–12]. Depending on the vibration mode and on the frequency, they exhibit a distribution of displacements and stress in the cross-section, especially at the interface substrate/adhesive, that could give information on the quality of the bonding. For example, Puthillath et al. [6] have selected the optimal Lamb mode to inspect the cohesive and adhesive defects in an aluminum–epoxy–titanium bonding, by measuring the amplitude decreasing of the mode in different samples. The study of a trilayers presents so a lot of difficulties, this is why in this paper, different bilayer samples are considered, where cohesive and adhesive aspects are taken into account, in order to obtain different controlled-

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strength bonds:

- The treatment of aluminum surface which is well known as one of the most important factor governing the adhesive strength of bond [13].

- The epoxy conversion linked to the curing cycle which has a strong influence on the mechanical behavior of the material. An epoxy network with a partial cross linking has many unreacted chain ends, a higher Young's modulus and a lower elongation and strain at break than a fully cured epoxy. It can be assumed that these differences will influence the strain of the bonding [14].

By combining these two factors we were able to create intentional weak bonds as well as strong bonds. Two evaluation parameters related to the interface are on the focus. In a first hand, an attenuation coefficient is measured for the samples discrimination. In a second hand, a rheological model based on springs distribution is developed in the aim to associate a couple of spring stiffness to a given sample.

2. Experimental part

2.1. Materials

The adhesive formulation is based on two components Epoxy system. Diglycidyl Ether of Bisphenol A (DGEBA, DER 331, Dow Chemicals) is cross-linked with an Aliphatic Diamine (Jeffamine, D230, Aldrich). The Epoxy and the Diamine are mixed at room temperature, at a stoichiometric ratio a/e equal to 1. The mixture is degassed to avoid air bubbles formation in the adhesive layer. 3 (glycidoxypopyl) trimethoxysilane also called γ -GPS, used for the chemical treatment is obtained from Aldrich. The chemical structures of the components are given in Table 1. The metallic substrate is an Aluminum alloy, A2024, in the form of 5 mm thick sheets.

2.2. Samples preparation

The studied bi-layer samples are made of a single aluminum plate of 5*200*200 mm³ coated on one side by an epoxy film of thickness d=0.5 mm. In order to obtain different adhesion levels, cohesive and adhesive aspects are considered: two conversions of the epoxy of 80% and 100%, and six different surface treatments of the aluminum substrate in contact with the epoxy, are performed, as summarized in Table 2. Finally, ten different bond conditions are evaluated.

Table 1
Chemical structures of components.

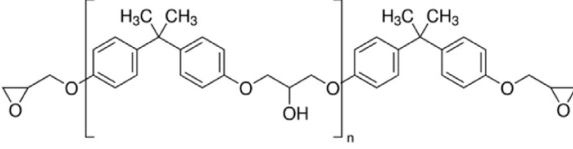
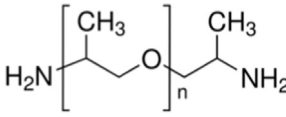
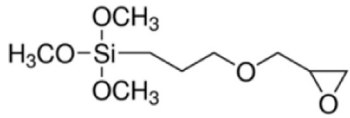
NAME	Chemical structure	Molar mass (g/mol)
Diglycidyl ether of Bisphenol A DGEBA		374
Polyetheramine D230		230
γ -GPS		236

Table 2
Set of samples manufactured.

Reference	Al surface treatment	Epoxy conversion
D-80	Degreased	80%
DSi-80	Degreased+silanisation	
DRq10-80	Degreased+sanded:	
DRq10Si-80	Degreased+sanded+silanisation	
D-100	Degreased	100%
DSi-100	Degreased+silanisation	
DRq10-100	Degreased+sanded	
DRq30-100	Degreased+sanded	
DRq10Si-100	Degreased+sanded+silanisation	
DRq30Si-100	Degreased+sanded+silanisation	

2.2.1. Surface treatments

Before coating, the aluminum substrates were treated as followed:

1. Degreasing (D): This treatment is performed in order to take off all the contaminant particles. Solvent degreasing is applied with a tissue soaked in isopropanol.
2. Degreasing and silanisation (DSi): The chemical treatment using a coupling agent is known to highly improve the level of the interfacial bond creating strong covalent bonds between the metal surface and the adhesive [14,15]. In our study, the samples are immersed 10 min in a 1 wt% solution of γ -GPS in distilled water. Prior to immersion, the pH solution is adjusted to 5 using acetic acid and the solution is stirred at room temperature for 1 h for the hydrolysis of methoxy groups. The silane-treated samples are heated for 1 h at 93 °C in an oven to allow condensation reaction [16,17].
3. Degreasing followed by sandblasting (DRq): The aim of this mechanical treatment is to remove the natural oxide layer and to create a rough surface in order to increase the apparent contact surface and its wettability, which could improve the level of the adhesion. In our case, the samples are sandblasted with corundum particles of different size.
4. Degreasing, sandblasting and silanisation (DRqSi): This treatment is the combination of chemical and mechanical treatments. The sandblasting is followed by the silanisation with the same protocol described previously.

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