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# Influence of adhesive bond line thickness on joint strength

P. Davies [a,*], L. Sohier [b], J.-Y. Cognard [c], A. Bourmaud [d], D. Choqueuse [a], E. Rinnert [e], R. Créac'hcadec [b,c]

[a] Materials and Structures group, IFREMER Brest Centre, 29280 Plouzané, France
[b] LBMS, Université de Bretagne Occidentale, 29285 Brest, France
[c] LBMS, ENSIETA, 29806 Brest, France
[d] L2PIC, Université de Bretagne Sud, 56321 Lorient, France
[e] Interfaces Group, IFREMER Brest Centre, 29280 Plouzané, France

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ABSTRACT

While the geometry of aerospace assemblies is carefully controlled, for many industrial applications such as marine structures bond line thickness can vary significantly. In this study epoxy adhesive joints of different thicknesses between aluminium substrates have been characterized using physico-chemical analyses (differential scanning calorimetry, DSC; dynamic mechanical analysis, DMA; spectroscopy), nano-indentation and mechanical testing. Thermal analyses indicated no influence of thickness on structure. Nano-indentation revealed no evidence of an interphase at the metal/epoxy interface, nor any change in modulus for different thicknesses, though Raman spectroscopy suggested there may be slight variations in composition close to the substrates. However, mechanical testing using the modified Arcan fixture indicated a significant drop in strength and failure strain under pure tension and a smaller reduction for tension/shear and pure shear loads as thickness increased. Examination of sections through joints did not indicate any physical reason for this, but numerical analysis of the stress state revealed larger stress concentration factors for tensile loading in thick joints, which may explain the thickness effect. It is recommended that joint thickness should be kept below 0.8 mm to avoid obtaining artificially low values with the Arcan test.

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## 1. Introduction

Adhesive bonding is now an established joining method which has been reviewed in detail recently [1]. It is a particularly attractive assembly technique for applications where weight gain is at a premium, and racing yachts are one such example. However, the large scale of structures such as boat hulls results in significant dimensional variations, so that it is not possible to achieve the thin bond lines and tight tolerances imposed in bonded aerospace structures. It is therefore essential to be able to characterize the influence of this parameter, and this was the aim of the present study. There have been several previous studies in this area using two approaches, based on either fracture mechanics or stress analysis. Kinloch [2] reviewed some early studies of both types. For lap shear specimens, the simple stress analyses for this geometry indicate a strong increase in failure stress with increasing joint thickness while measurements and finite element analysis indicate much lower sensitivity to this parameter [3]. In early studies on bond line thickness Bascom and colleagues [4] and then Kinloch and Shaw [5] used linear elastic fracture mechanics tests to characterize the crack propagation resistance of joints up to 3 mm thick. They found an optimum joint thickness around 0.5 mm, and postulated that there is competition between a constraint mechanism, due to the rigid substrates, at low thickness, resulting in high tensile stresses, and the amount of dissipation in the plastic zone which increases to a maximum then reduces at higher thickness. The following expression was proposed for the optimal joint thickness $h$, based on the fully developed plastic zone radius ($r_p$), for plane stress and linear elastic fracture mechanics [5]:

$$h = 2r_p = \frac{1}{\pi}\left(\frac{EG_c}{\sigma_y^2}\right) \quad (1)$$

where $E$ is the adhesive modulus, $G_c$ the critical strain energy release rate and $\sigma_y$ the yield stress. A peak in toughness versus bond line thickness can be expected when $r_p$ equals the latter. These results were cited by Kinloch and Moore [6], who presented further data which showed the same trend. More recently Kawashita et al. presented peel test data from aluminium joints with bond line thicknesses of 0.1, 0.25 and 0.4 mm, below the optimal thickness, for two epoxy adhesives [7]. Measured toughness increased with thickness and a reasonable fit was obtained between test results and their LEFM model. Mall and Ramamurthy used double cantilever beam specimens to examine fracture and crack growth under cyclic loading in joints of

* Corresponding author. Tel.: +33 298 22 4777; fax: +33 298 22 4535.
*E-mail address:* pdavies@ifremer.fr (P. Davies).

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different thicknesses [8]. DCB joints with different adhesive thickness showed similar thresholds at lower crack growth rates, whereas a thicker adhesive layer resulted in an improved resistance to the crack growth for high propagation rates. Gleich et al. also used a fracture mechanics approach, to show that the stress intensity factors, after an initial decrease in the low bond line thickness range, increased with increasing bond line thickness [9]. In another study, using the more traditional stress-based approach, Tomblin et al. [10] presented results from thick adherend shear test (TAST) and thin adherend lap shear specimens with adhesive thicknesses in a wide range from 0.4 to 3 mm. Their aim was to produce stress–strain data for design of secondary bonded assemblies in general aviation applications, for which joints may be thicker than the standard 0.25 mm thickness. They noted a decrease in apparent shear strength with increasing joint thickness for the three adhesives tested on aluminium substrates with both tests. TAST specimens gave consistently higher values than thin adherend lap shear specimens at all bond line thicknesses, due to the development of peel stresses in the latter. Grant et al. also presented results from tests on lap shear specimens which showed a linear drop in failure load as bond line thickness was increased from 0.1 to 3 mm, and they attributed this to an increase in bending stress for the thicker adhesives [11]. Taib et al. recently showed results for L-section joints with adhesive thicknesses of 0.127, 0.635 and 2.54 mm [12]. Failure loads dropped from 8.27 to 3.9 kN as joint thickness increased, and this was attributed to a change from plane stress to plane strain states. Finally, Jarry and Shenoi examined 1, 5 and 10 mm but strap metallic assemblies bonded with a methacrylate adhesive and found similar strengths for 1 and 5 mm but significantly lower values for the thickest bond line [13].

This summary of some of the previous work on bond line thickness, and the fact that many of the papers cited are very recent, underlines the importance of this subject. There is a tendency for measured failure stress to decrease with increasing bond line thickness, but interpreting variations in properties can be quite complex as various factors may intervene to modify the behaviour of joints as their thickness is increased:

- First, the nature or dimensions of defects may vary with bond line thickness. Visual and microscopic examination can be used to check this effect.
- Second, the adhesive structure may change as thickness increases. This may be caused by differences in cure conditions for example. Heterogeneous thermal behaviour, such as exotherm dissipation, will depend on the proximity of conductive substrates. Thermal analyses or local property measurements may enable such variations to be detected.
- Third, the adhesive/substrate interface properties may be modified as thickness increases. This may be due to internal stresses developing at this interface [14], to migration of species from the substrates into the adhesive (oxides) or to changes of stoichiometry within the adhesive near the substrate. Roche and colleagues have examined these phenomena in detail [15]. Many techniques have been used to detect interphases, based on changes in chemical state (by infra-red spectroscopy or micro-thermal analysis for example [16]) or mechanical properties (tensile, nano-indentation or even laser acoustic methods [17]).
- Fourth, the energy dissipating mechanisms (plasticity, damage development) may be modified by changing the distance between the substrates. Careful mechanical testing can be used to illustrate this.
- Finally, the change in specimen geometry with increasing bond line thickness may cause a change in the stress state within the joint so that tests on specimens with different thicknesses are not measuring the same properties. In order to examine this detailed stress analysis of the joint is required.

In the present paper these different factors will be examined using various techniques, in order to conclude on the influence of joint thickness on the mechanical behaviour of aluminium substrates bonded with a tough epoxy adhesive. Here we focus mainly on the non-linear behaviour of the adhesive rather than crack propagation.

## 2. Materials

The adhesive examined here is a two-part system. An amount of 100 parts by weight of a diglicidyl ether of bisphenol A (DGEBA) epoxy pre-polymer are mixed with 40 parts of trioxatridecane diamine (TTD) hardener, previously marketed as *Redux 420,* now *Araldite 420* supplied by Huntsman. This adhesive has been widely used for many years, in both the aerospace and marine industries. It contains some spherical fillers, estimated from burn-off to represent around 8% by weight. Energy dispersive X-ray (EDX) analysis in the electron microscope indicated these to be solid glass spheres as will be described below. The choice of a commercial adhesive for this study, rather than a model epoxy, was made so that the results would be of direct interest for industrial assemblies. However, the complex formulation does make interpretation of results more complicated. The substrates are aluminium 2017 grade alloy.

## 3. Specimen preparation

Adhesive film samples, for differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA) and tensile tests, were produced by mixing the adhesive and hardener and casting films of different thicknesses between two acetal blocks, with spacers to define joint thickness. Bonded aluminium assembly specimens for mechanical testing in the Arcan fixture were prepared in two special jigs, enabling 12 specimens to be bonded at a time, one of which is shown in Fig. 1. Surface preparation of the substrates was abrasion with 120 grade abrasive paper, an acetone wipe to remove dust particles followed by careful drying. Substrate surface roughness Ra was measured to be between 1.7 and 2.2 μm.

Some specimens were tested in the Arcan test fixture, samples for DSC were then removed directly from fracture surfaces. Others were sectioned by a high pressure water jet into three parts, which created six surfaces for microscopic inspection and nano-indentation, Fig. 1b. The cure cycle for all samples was 24 h at 20 °C, followed by 4 h at 50 °C. This was chosen as it is a commonly applied cycle in racing yacht construction. Higher cure temperatures are not easy to apply in boatyards where the structures to be assembled may be tens of metres long. This cure cycle has been shown in a previous study to result in a $T_g$ value around 50 °C [18].

## 4. Experimental techniques

In order to establish whether the polymer structure and its interface with the substrates were affected by changing the joint thickness various analyses were performed before the mechanical properties were measured. These included microscopic examination, thermal analysis, nano-indentation and Raman spectroscopy. Then tensile tests on cast films and Arcan tests on bonded assemblies were performed.

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