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Adhesively bonded functionally graded joints by induction heating

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ABSTRACT

The main objective of this work was to develop an adhesive functionally modified in order to have mechanical properties that vary gradually along the overlap, allowing a more uniform stress distribution along the overlap and to reduce the stress concentrations at the ends of the overlap. This allows for a stronger and more efficient adhesive joint. The adhesive stiffness varies along the overlap, being maximum in the middle and minimum at the ends of the overlap.

In this study, grading was achieved by induction heating, giving a graded cure of the adhesive along the joint. The functionally graded joint was found to have a higher joint strength compared to the cases where the adhesive is cured uniformly at low temperature or at high temperature. Analytical analysis was performed to predict the failure load of the joints with graded cure and isothermal cure.

1. Introduction

The main advantage of adhesive joints is that the stress distribution is more uniform than with the other traditional methods of fastening such as bolts or rivets. This permits to work with smaller load bearing areas leading to weight savings. This is the main reason why adhesives were initially used in the aeronautical industry where the weight is a crucial matter. Nowadays, adhesives are used in other industries, automotive industry being the one of the largest growing markets. That is obviously because the car industry is looking at ways to reduce fuel consumption by means of a weight reduction [1].

One of the most common types of joints is the single lap joint, due to its simplicity and efficiency. When analysing this type of joint, the main problem associated with it is the stress distribution (peel and shear) in the adhesive along the overlap. The stresses along the overlap are not uniform, being concentrated at the ends of the overlap. That is why one of the main areas of investigation in the field of adhesive bonding is to develop ways of reducing these stress concentrations for a more efficient adhesive joint strength and additional weight savings. In the literature, several methods have been proposed but none provide a uniform stress distribution in the adhesive [2–5].

Joint strength optimisation can be obtained through modifications of the adherend geometry, the adhesive spew fillet geometry, mixed adhesive joints, or adhesive joints with functionally graded materials. An important factor that affects the critical stresses is the geometry of the adherend corners at the ends of the overlap. Adherends with geometric modifications by inclusion of a taper in the adherend is a way to decrease the stress concentration at the ends of the overlap; the concentrated load transfer can be more uniformly distributed if the local stiffness of the joint are reduced and the strength of the joint increases substantially [6–8]. Joints with rounded adherends at the ends of the overlap reduce significantly the shear and peel [9–12]. Also, modifications of the joint end geometry with a spew fillet provide a great reduction in the adhesive stresses (shear and peel) concentration, gives a smoother load transfer over a larger area and alters the stress intensity factors [13–17]. However, the complexity of the geometry increases and that is not always possible to realise in practice.

The use of more than one adhesive has been proposed to modify the mechanical properties of the adhesive along the overlap. This technique consists in using a stiff and strong adhesive in the middle of the overlap and a flexible and ductile adhesive at the ends of the overlap to relieve the high stress concentrations at the ends of the overlap [7,8,18–21]. This allows to have a more uniform stress distribution which leads to joint strength increases in relation to a stiff adhesive alone [18, 22–26]. Although this approach has been discussed theoretically, there have been relatively few published experimental demonstrations of a practical method that yields significant improvements in the joint performance. Fitton and Broughton [18] studied theoretically and experimentally that the variable modulus adhesive is an effective way of reducing stress concentration and especially peel. The study has shown that variable modulus bondlines can reduce stress concentrations, increasing joint strength and change the

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mode of failure. da Silva and Adams [16] investigated theoretical and experimental dual adhesive metal/composite joints and showed that there is a real improvement in joint strength, especially if the difference of coefficients of thermal expansion is high. Marques and da Silva [8], da Silva and Lopes [21] and Marques et al. [27] have shown that the mixed adhesive technique gives joint strength improvements in relation to a brittle adhesive alone in all cases. If the ductile adhesive has a joint strength lower than that of the brittle adhesive, a mixed adhesive joint with both adhesives gives a joint strength higher than the joint strength of the adhesives used individually. The mixed adhesive joint technique can be considered a rough version of a functionally graded material.

The ideal would be to have an adhesive functionally modified with properties that vary gradually along the overlap allowing a true uniform stress distribution along the overlap. Ganesh and Choo [28], Boss et al. [29] and Apalak and Gunes [30] have used functionally graded adherends instead of functionally graded adhesives. Ganesh and Choo [28] and Boss et al. [29] used a braided preform with continuously varying braid angle and the variation of the braid angle measured to realistically evaluate the performance of adherend modulus grading in single-lap bonded joint. An increase of 20% joint strength was obtained due to a more uniform stress distribution. Apalak and Gunes [30] studied the flexural behaviour of an adhesively bonded single lap joint with adherends composed of a functionally gradient layer between a pure ceramic (Al_2O_3) layer and a pure metal (Ni) layer. The studies are not supported with experimental results and the adhesive stress distribution was not hugely affected.

There have been some attempts to modify the adhesive along the overlap. Sancaktar and Kumar [31] used rubber particles to modify locally the adhesive at the ends of the overlap and with this technique increase the joint strength. More recently, Stapleton et al. [32] used glass beads strategically placed within the adhesive layer in order to obtain different densities and change the stiffness along the overlap. In this study it was shown that with this technique a significant reduction in peel stress is obtained. The mixed adhesive and the physical modification of the adhesive with adhesive doped by rubbery particles or glass beads, can be considered a rough version of a functionally graded material. However, the dispersion of particles (rubber particles or glass beads) throughout the adhesive layer is a complex bonding technique which is inconvenient to perform in practice.

In this study a technological process to functionally modify the adhesive along the overlap allowing a true uniform stress distribution was developed. The adhesive stiffness varies along the overlap, being maximum in the middle and minimum at the ends of the overlap for a uniform load transfer. This functionally graded adhesive was achieved based on a differentiated cure process. Adhesives are generally cured in an oven or in a hot press uniformly giving an adhesive with uniform properties along the overlap area. If the adhesive can have several degrees of cure, then a gradient in the rigidity of the adhesive along the overlap can be obtained, as was recently shown by Carbas et al. [33,34]. The localised heating was done with induction heating. Induction heating is a fast heating method because it focuses heat at or near the adhesive bondline. The most important advantages of induction heating are assembly speed and the fact that an entire assembly does not have to be heated to cure only a few grams of adhesive (the confined area). This technique can be easily implemented in the industry and very efficient (fast bonding, heating only the area of interest, curing equipment more compact, decreasing of the energy consumption).

The present study demonstrated the high performance of functionally graded joints obtained by induction heating when compared with adhesive joints cured isothermally at low or high temperature. In order to predict the failure load value of joints cured isothermally, simple numerical analysis were used (as Volkersen´s analysis [35] and global yielding criterion [36]). A simple analytical analysis proposed by Carbas et al. [34] was performed to predict and assess the possible effectiveness of a graded joint concept.

2. Experimental details

2.1. Materials

According to previous studies [33,34], adhesives were selected in order to have an adhesive with a high variation of the mechanical properties as a function of the cure temperature. The adhesives selected are two bi-component epoxy adhesives which mechanical properties were determined as a function of the cure temperature by Carbas et al. [33,34].

The first adhesive studied was Araldite® 2011 (Huntsman, Basel, Switzerland). The chemical formulation of this adhesive is bisphenol A for the epoxy resin and polyaminoamide for the hardener.

The second adhesive studied was Loctite Hysol® 3422 (Henkel, Dublin, Ireland). The chemical formulation of this adhesive is bisphenol A diluted with bisphenol F in for the epoxy resin, and 3-Aminopropylmorpholine and polyoxypropylene diamine for the hardener.

Typical stress–strain curves of the adhesives Araldite® 2011 and Loctite Hysol® 3422 as a function of the cure temperature are shown in Fig. 1.

The adherend selected was a high strength steel (DIN C65 heat treated) with (tensile strength of the adherend) $\sigma_{ys}=1260$ MPa and $E=210$ GPa to avoid plastic deformation of the adherend [38–40].

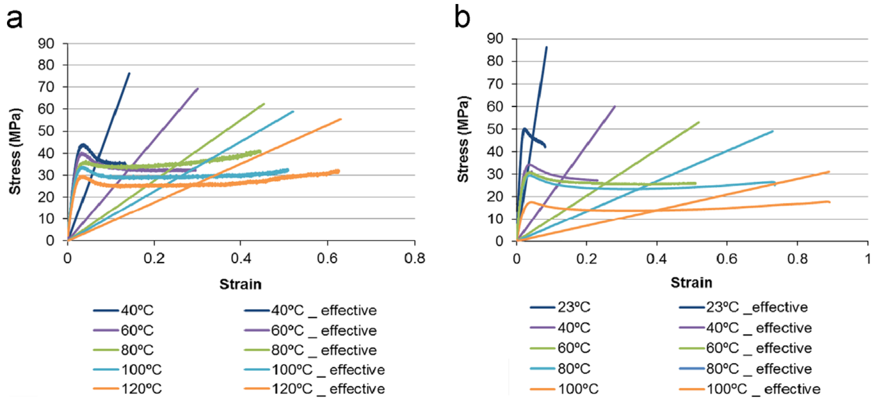

Fig. 1. Tensile stress–strain curves of Araldite® 2011 (a) and Loctite Hysol® 3422 (b) adhesives as a function of the cure temperature.