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Bonded joints of dissimilar adherends at very low temperatures - An adhesive selection approach

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ABSTRACT

Maintenance, repair and overhaul companies have been reporting corrosion failure events in the Airbus A320 CFM56-5b intakes. These intakes are attached to the power plant frame by a dissimilar material bonded joint, where liquid shim adhesive is used to avoid the dielectric formation between dissimilar materials. In previous works, the authors reported that the A320 intakes corrosion is a result of the adhesive inability to avoid the dielectric formation, which is a result of micro-cracks formation within the adhesive layer. The main reason that lead to these cracks is the adhesive aging and thermal cycling at very low temperatures, which quite often reach values lower than −50 °C. This paper studies the effect of negative thermal loading on dissimilar materials bonded joints. Two epoxy adhesives are studied and compared, namely the Hysol EA-934, which is the adhesive currently used in the A320 Airbus intakes, and the Hysol EA-9394, a second generation adhesive candidate to replace the actual adhesive. A numerical study was performed in order to simulate the adhesive joint using a finite element analysis commercial package, where several hypotheses were explored. These hypotheses where focused on the effects of several factors on the adhesive layer stress distribution. Factors such as temperature range, boundary conditions, variation of the coefficient of thermal expansion with temperature, and interfacial cracks between the adhesive layer and dissimilar adherend materials were analyzed. Results show that very low temperatures have a negative impact on the adhesives strength and micro-cracks formation may result from thermal loads below zero degrees Celsius, even for adhesives without any aging. Moreover, low temperatures in dissimilar materials bonded joints may create stress states that surpass the adhesive lap shear strength. Some conclusions are drawn regarding adhesive selection for dissimilar materials bonded joints in order to overcome these issues.

1. Introduction

Several complex repair events related to adhesive failure of dissimilar bonded joints have been reported by maintenance, repair, and overhaul companies. Particularly, the Hysol EA-934, a first generation adhesive, has been related to galvanic corrosion between the Al 2024-T3 and the Ti6Al4v titanium alloy, which are two dissimilar adherend materials [1]. These two metallic materials have different electro-negativities, which is a suitable condition to spark the galvanic corrosion process if a dielectric between them is created. Besides the gap filling task, the main feature of the Hysol EA 934 adhesive is to avoid the direct contact between dissimilar metals and create a barrier to dielectric promoters such as moisture, water, and corrosive agents. Usually, aerospace epoxy adhesives are able to endure very high temperatures, they may cure at a wide range of temperatures ranging from 70 to 177 °C. Moreover, they are able to maintain their performance beyond the adhesive glass temperature, they do not melt and in many cases, service temperatures higher than their glass temperature increases their ductility and peel strength [2]. However, high temperatures are used in repair actions, for example the adherends separation of an adhesively bound can be made by heating the joint over 200 °C in order to brake the chemical links and to allow the mechanical separation using a palette-knife, which is difficult task to make and normally a non-advised procedure in aerospace due to side effects in the structure. On the other side, low temperatures can be problematic for some adhesives, especially in the case of the so-called first generation adhesives. Low temperatures significantly promotes the reduction of these

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adhesives strength by reducing their ductility. One evidence of the low temperatures effect on the first generation adhesives strength is commonly experienced in the shop during repair actions. The Airbus A320 structural repair manual (SRM) demand the use of dry ice to brake the adhesive chemical bounds. The dry ice is placed over the bonded joint and with a palette-knife the two adherends are easily separated. This process is much more easy to perform and safe than the heating/palette-knife process. Moreover, no side effects such as warpage or change on the metallic parts quenching state are created. The problem is that during service, aircraft easily experiences temperatures lower than −50 °C. These very low temperatures make the adhesive brittle and weakens their chemical bonds during service. In this situation the adhesive integrity can be easily reduced due to the structural forces transmitted to the bonded joint, which can create micro-cracks in the adhesive layer. The hot temperatures required to break the adhesive bond are unlikely to be found in the field (up to 200 °C), normally aircraft structures are not subject to such high temperatures. However, very low temperatures able to break adhesive bonding can be often experienced by aircraft, especially in the case of first generation adhesives. In literature, it can be found several works related to dissimilar materials joints. The most common examples are magnesium to aluminum, and composite to aluminum adhesive joints [3–5]. In these works, the research focus has been on interface cracks, high and low temperatures, residual stresses, and failure characterization [6–10]. The effect of cryogenic temperatures on the adhesive layers, especially in micro-cracking formation, has been a subject of intense research [11–14], however most of the results cannot be extrapolated from one adhesive to another. Similarly to the low temperature topic, fracture mechanics is also a very active topic in adhesives characterization. The focus has been on interface cracks, crack initiation, crack growth, and crack propagation [4,15–19]. In many of these experiments, the single lap joint of similar and dissimilar adherends uses the ASTM D1002 standard to evaluate thermal effects and adhesive crack characterization [20–22]. Also, the single lap joint has been widely used in literature to numerical modeling adhesively bonded joints, including simulation of interfacial cracks [23–25]. Developments on these simulations has been an important outcome that has been supporting the development of failure criteria of adhesive joints under complex loadings [26]. This paper studies the Hysol EA-934, and Hysol EA-9394 mechanical performance in a dissimilar joint made of two dissimilar metals typically found in aerospace structures, namely an aluminum alloy, and a titanium alloy. It was found that there is a lack of knowledge in literature regarding the behavior of these two adhesives in bonded joints of dissimilar materials, especially at very low temperatures. Very few works can be found in literature regarding the Hysol EA-9394 mechanical behavior [25], but none of them focus its behavior in dissimilar materials joints at low temperatures. On the other hand, results for the EA-934 adhesive are also very scarce in literature. The Hysol EA-934 adhesive is quite old, it was launched in the market for more than 20 years and starts to appear in the aeronautic industry some concerns about its failure to barrier the galvanic corrosion between dissimilar metals.

2. Materials and methods

2.1. Materials

In this study two adhesives are analyzed in order to understand and predict their mechanical behavior under very low temperatures in the case of dissimilar materials joints. The two adhesives are the Hysol EA-934 and the Hysol EA-9394 from Henkel, a worldwide German company with more than 140 years and a strong presence in the aerospace industry. These adhesives are the so-called liquid shims and are suitable for aerospace applications, especially in the rib-to-skin assemblies. They are epoxy-based materials and their main function is to eliminate gaps between composite parts, this gaps are usually less than 3 mm. For gaps wider than 3 mm solid shims are advised. The usual key features when selecting liquid shim adhesives are the pot life (working life or gel time), compressive strength, resistance to cyclic fatigue and optimal viscosity. Table 1 shows the Hysol EA-934 and Hysol EA-9394 mechanical properties at room temperature, 25 °C. Their Young's modulus and strength are very similar.

Fig. 1 shows the adhesives stress-strain behavior at room temperature (25 °C). These results were obtained using the ASTM D618 standard, and they can be found in Refs. [27,28].

The EA-9394 adhesive has lower stresses at higher strains than the EA-934 adhesive. This result makes the Hysol EA-9394 adhesive a good candidate to be used in dissimilar bonded joints because it is able to accommodate higher strains with lower stresses, it is a more ductile adhesive. Dissimilar bonded joints experience relative strains in the bond region, therefore, a good adhesive for dissimilar material bonded joint must be able to accommodate a wide range of contact strains.

Table 2 shows the lap shear strength and the coefficient of thermal expansion variation with temperature for the Hysol EA-934 and Hysol EA-9394 adhesives.

Fig. 2 depicts the data shown in Table 1. Fig. 2(a) shows the variation of the EA-934 and EA-9394 lap shear strength with temperature. From this graph one can conclude that the Hysol EA-9394 adhesive has a lap shear strength 15% higher than the Hysol EA-934. Fig. 2(b) shows the coefficient of thermal expansion of both adhesives, the Hysol EA-9394 has a coefficient of thermal expansion 40% lower in average than the Hysol EA-934. This feature and the higher capability do accommodate higher strains reinforce the hypothesis in which the Hysol EA-9394 has improved capabilities to be used in dissimilar materials bonded joints.

Table 3 shows the mechanical properties of the two dissimilar metals considered in this study, namely the 2024-T3 aluminum alloy and the 6th grade titanium alloy Ti6Al4v. These two materials are widely used in aircraft structures and often are bonded with the Hysol EA-934 epoxy adhesive.

2.2. Numerical simulations

This study is strongly based on numeric simulations of the ASTM D1002 specimen test. The numerical simulations were done using ANSYS, a FEM commercial package widely used by academia and industry. The numerical model was developed based on the guidelines given in [31]. The book provides technical know-how to simulate a variety of adhesively bonded joints using ANSYS. Moreover, issues regarding convergence, mesh, loads, etc. were already validated in this book. The study main objective was to analyze the mechanical behavior of the dissimilar materials bonded joint within the temperature range −50 °C to 22 °C. This joint comprises three different materials, namely an adhesive, an aluminum alloy, and a titanium alloy, these materials were already presented in the previous sub-section. All materials have different coefficient of thermal expansion (CTE), thus this joint will experience different stress patterns within each material, the strains at contact regions will be the same for both materials in contact but stresses (assuming non slip in the materials interface) at each material will be different. Fig. 3 shows the specimen geometry used in simulations, the adhesive layer has a 0.2 mm thickness, the upper subtract is made of 2024-T3 aluminum alloy, and it is 3 mm thick and 120 mm long. The lower subtract is made of titanium and also is 3 mm thick, and 120 mm long.