MODELING CHALLENGES IN CYCLIC HYDROTHERMAL AGING OF AIRCRAFT LIGHTNING PROTECTION

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Abstract
The recent transition to full composite fuselages is a major breakthrough in aeronautical design. To ensure satisfactory lightning protection, the electrical properties of the primary composite structure need to be improved and a design solution lies on bonding a metallic fishnet to the fuselage. An important issue is the prediction of the aging behavior of this top layer when exposed to severe aging conditions representative of flight environment. Multiple aging mechanisms affect this top layer made of thermoset resin and metallic fishnet with complex geometry and a first modeling strategy is a necessary starting point to better understand its evolution. This paper describes the overall phenomenology and the different mechanisms that can be expected in such a structure.

1 Introduction

Despite Carbon-Fiber Reinforced Polymers (CFRP) being used since more than 50 years in non-primary aircraft components, only few attempts have up to now been made to generalize the use of these materials to primary structural part. Along with the new generations of aircrafts comes a major innovation: the composite fuselage.

The technological choices differ between the major aircraft suppliers. Boeing is making the choice of an integral composite fuselage based on full composite barrels for the B787; Airbus will limit the use of advanced composites to some fuselage sections with panel-based barrels (each barrel is made of the assembly of different sub parts) [14]. In both case, large sections of the aircraft will be based on thermoset carbon-fiber materials.

This strategy is motivated by (1) reducing the weight of the final structure - for increased fuel efficiency- (2) processing considerations - better integrations of multiple functions, reduction of the assembly cost - (3) simplified maintenance - the better properties of composite materials in fatigue allowing to reduce the frequency of maintenance inspections.

Yet, new challenges come with this technological choice, one of the most critical being lightning protection. Using an integral metallic airframe and fuselage was an efficient way to ensure lightning protection. Indeed in such a case, a Faraday cage is naturally created and the

lightning gets transmitted through the fuselage directly to the ground resulting in an efficient protection of the structure. CFRP are characterized by very poor electrical properties due to the matrix, which is an excellent dielectric. Despite the carbon fibers being quite good conductive materials, with a resistivity around 10e-5 Ohm/m [32], the electrical conductivity of the resulting prepreg is very low [32]. When lightning strikes, the material is unable to dissipate the electrical energy. This might induce a strong shock wave and localized heating. From a mechanical point of view, the shock wave might lead to local fragmentation while the localized heating might induce the pyrolysis of the resin around the impact point [20]. Both these effects endanger the structural integrity of the fuselage [12,13,15].

Then, the key idea is to design a specific lightning strike protection (LSP) that would restore the electrical conductivity. Current technologies are based on introducing a specific coating on the top surface. Three practical configurations are currently under consideration (1) a metallic fishnet is bonded separately as the outermost laminate layer [20] (2) a metallic wire network is co-woven with the carbon fiber in a prepreg fabric (3) the matrix of the top layer is doped with carbon nano tubes that highly enhances the electrical conductivity even at low nano particle content. Here, we place our study in the first configuration (copper or aluminum fishnet), which is an actual industrial choice.

With such a choice, this top layer appears to be a complex heterogeneous metal/polymer structure. Furthermore, it will be the first layer to be actually exposed to the environmental flying conditions: repeated thermo-mechanical cycles going from very low to warm temperature (for such composites) along with moisture. All together, these phenomena might endanger the structural integrity of this complex metal/polymer network. A rigorous modeling approach is thus necessary to fully capture this process and optimize the metallic electrical reinforcement (its geometry, its material) and to reduce the potential initiation of a crack.

This paper discusses some key points of the underlying mechanisms: moisture aging of polymers, aging of polymer/metal interface and thermo-mechanical fatigue of polymers. Though the considered technological application is very specific to the aeronautical industry, most of the underlying key mechanisms have been studied in different fields, from structural engineering to microelectronics (where the same concerns about aging of metallic/polymer interfaces exist). We aim to give here an overview of the general understanding of these mechanisms that can serve as a basis for a pragmatical and robust modeling.

2 Some highlights about short-term hydrothermal aging
1.1 Material system
The lightning protection layer of interest is made of a metallic fishnet provided by Dexmet technologies embedded within an epoxy coating layer (Fig. 1). Exact details are not provided for confidentiality. The objective is to build a generic prediction tool for such lightning protection layers, in which metallic expanded foils (copper or aluminum) are embedded within a surfacing film made of an epoxy resin.
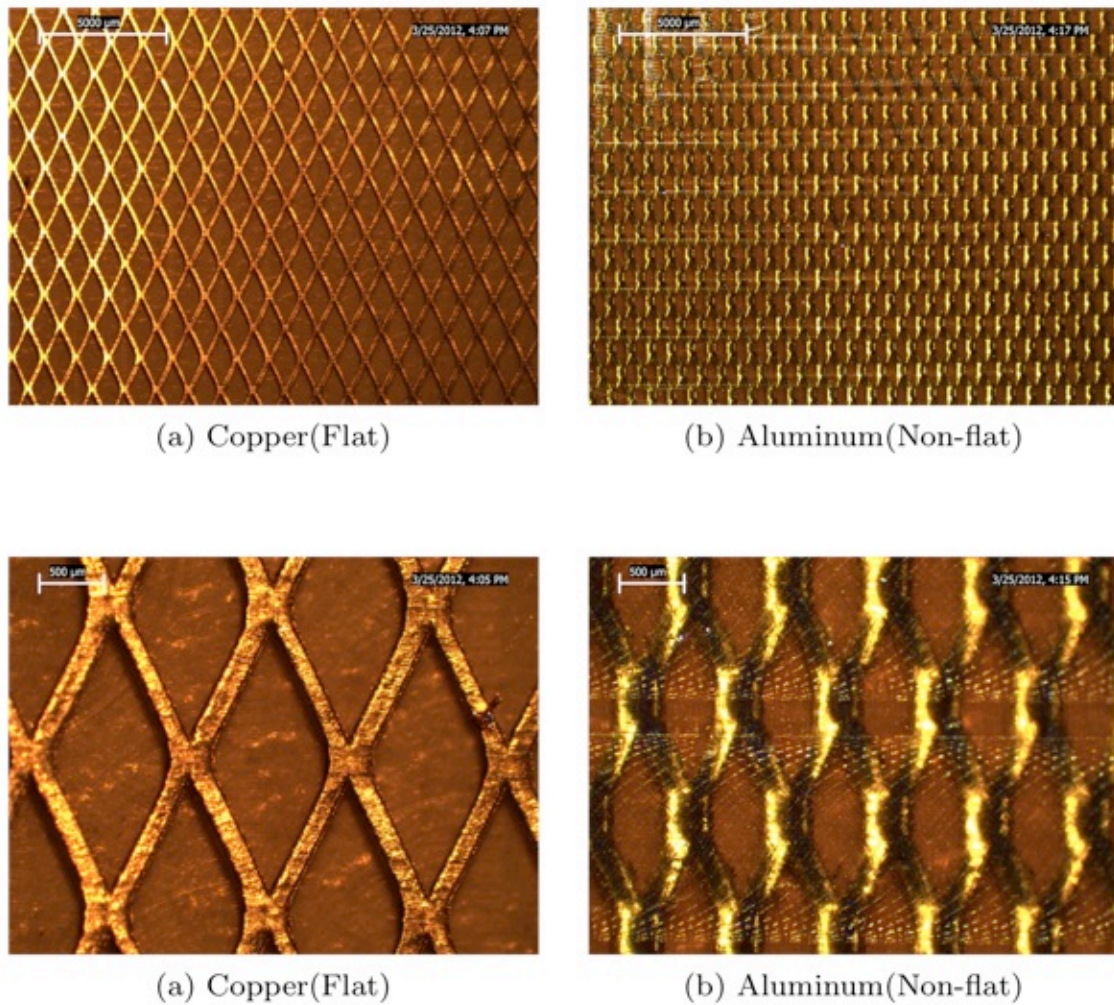
Figure 1. Fishnet samples of copper and aluminum: flat and non-flat.

During aging, this material system is submitted to a cycle representative of flying conditions: thermal cycling -65F/160F with 90% moisture. These testing conditions induce complex damage due to the superposition of multiple phenomena: moisture aging of the polymer matrix (reducing its mechanical properties), chemical aging of the polymer/metal interface (decreased toughness of the interface that might initiate interfacial cracks), mechanical fatigue of both the matrix of the interface due to severe thermal cycling

1.2 General phenomenology

Moisture aging of the epoxy system. Many studies have considered the modification of pure epoxy systems induced by moisture exposure or immersion. Most of these do focus on isothermal conditions, generally at high temperature. It thus differs from our study in which thermal cycling is considered, from extreme cold to elevated temperature. Yet, a short literature review of these classical studies is worthy to understand the major underlining phenomenology in which several stages can be clearly identified.

3

Two approaches of water interaction with epoxy network have emerged over the time. First approach assumes that water molecules reside in the micro-pores of excess free volume of epoxy network, for this approach bonding between water molecules and epoxy network is insignificant. While second approach is based on the assumption that water molecules make hydrogen bonds with polar groups of epoxy network; hydroxyl and amine groups. Zhou, J. M. and J. P. Lucas studied the nature of water in epoxy absorbed at different temperature by immersing the epoxy samples in water, using solid state (NMR) spectroscopy and concluded that more of water molecules bind with epoxy network through hydrogen bonding. They classified bound water in two types Type I and Type II . Type I making the category of water molecules which are bound making only one hydrogen bond and Type II making multiple bond and providing some type of secondary cross linking in epoxy network [38]. During the first stage of moisture exposure which is characterized by moisture uptake into free volume micro-pores and single hydrogen bonds of water molecules with hydrophilic groups, diffusion rate is very high depending on environmental water content. The epoxy system experiences a strong degradation of its material properties. Monitoring the glass transition temperature Tg is a common observation. It decreases after a very short moisture exposure time [36,38]. As so, Zhou and Lucas [38] reported a rapid drop of Tg around 45% for an epoxy system under immersion conditions at 90oC. This is a common observation that comes with a strong reduction of the mechanical properties [28]. According to Alessi et al. [3], the destruction of the weak inter chains bonding during the first stage results in increasing the mobility of the polymer chains hence plasticization; then, the polymer tends to reduce its free volume by moving towards its equilibrium state. This phenomenon of free volume reduction is known as volumetric relaxation. This can be seen as a specific family of physical aging. Experimental evidence show that this short-term aging process is almost fully reversible as the initial Tg is recovered in dried samples after a desorption process [28,38]. Adamson [2] clearly demonstrated that the resin volume change during this stage is only a fraction of the total volume of absorbed moisture. Indeed, water first diffuses into the material and mainly tends to accumulate into the initial voids and porosity. A small fraction of the absorbed water introduces a swelling effect by forming single hydrogen bonds with the epoxy backbone while destroying the initial Van Der Waals bonding. At the end of this first stage, the water uptake tends to slow down and can, in some situation, stabilize. The transition to this second stage is reported in many experimental observations [22,38].

During this second stage, Tg (as well as other major material properties) tends to slightly recover with time (a comprehensive set of experiments can be found in [38]). A common explanation lies in the creation of double hydrogen bonds (type II bounds between water and hydrophilic groups such as hydroxyls and amines). These result in a "secondary cross-linking" of the epoxy backbone [3]. Similar observations have been done by Zhou [38] who studied the thermal activation of this mechanism (the recovery of the glass transition temperature is lower with longer aging time and higher temperatures [38]). Type II bound water molecules have higher activation energy as compared to Type I water molecules; more energy is needed to release this water uptake, it becomes much more difficult to recover the initial material properties by drying the samples [22], making in practice this process non-reversible.

Moisture aging of the epoxy/metal interface. The effect of aging at the interface follows a different mechanism from the bulk diffusion found in the respective materials. Metal/polymer systems generally exhibit a strong reduction of their bond strength in case of moisture and temperature. Debonding is a primary concern when considering metal/resin adhesive joints. It was observed that the bond strength due to moisture (immersion at 90oC)

reduced and leveled at half the original value [8]. The primary mode of moisture transfer within the interface is the seepage/capillary diffusion [5,35] along the interface. K L Chan [5] showed that the interfacial diffusion coefficient was higher than the bulk diffusion coefficient which suggests that the interfacial degradation was higher than the bulk degradation which shows that the primary locus of damage would be at the interfaces. Previous studies also point out that the cohesion strength (strength of the bulk epoxy) degradation is reversible while the joint strength (strength of the interface) degradation is partly irreversible [8-10,30]. Only 80 to 85% of the strength is recovered [10]. Water molecules aggregates at hydrophilic sites which disrupts the secondary hydrogen bonds between the polymer and the substrate at the boundary layer [8] and this is found to be reversible. This results in the displacement of the epoxy from the metal and the formation of a water layer in-between them [10,30]. The irreversibility is caused due the covalent bond rupture by stress hydrolysis at the interface [9,10]. Experiments show that high temperature enhances the rate of diffusion of moisture into the interface which further increases the debond extension [11,26]. Thus the interface region becomes vulnerable to external dynamic stress, which easily relaxes and deforms this region [27].

The Interfacial debonding due to hygrothermal aging can be characterized by fracture models, which depicts delamination as crack propagation along the interface [21,26]. The model depicts two regions: i) Region I where the debond growth rate is dependent on the strain energy release rate (GA) and the rate of reaction between the water and the interface, ii) Region II in which it is linearly dependent on the partial pressure of vapor.

Fatigue aging of the epoxy system and of the epoxy/metal interface. The primary cause of fatigue failure is the formation of micro-cracks/craze on the surface which propagates with further cycling and results in failure [16,33,37]. During the cyclic aging, the thermal residual stresses vary with the cycling temperature. This causes cyclic softening of the polymer. Also the mismatch in the thermal expansion coefficients between the two different materials will cause local stress concentrations at the interface, which would serve as focus points for the initiation of these micro-cracks [27]. This will induce the mechanical fatigue of both the bulk resin and the metal/matrix interface. Furthermore, this typical stress cycle evolves during the aging process due to the moisture absorption and the development of non-reversible swelling. It was observed that the structural inhomogeneity always presented stress concentration points within the material and thus the fatigue crack propagation dominates the total fatigue life [17]. Since the material follows different modes of damage at different times, a cumulative damage model which defines the microscopic fatigue damage as a deterioration of macroscopic properties such as stiffness or strength [7,34,37] should be defined.

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