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Thermal cycling of (heated) fibre metal laminates

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ABSTRACT

Fibre metal laminates with integrated heater elements have a promising potential as de- or anti-icing systems in aircraft structures. The alternating metal and composite lay-up in fibre metal laminates seems ideal for the development of a multifunctional skin with embedded heater elements. However, the long term durability needs to be carefully examined.

A unique thermal cycling setup has been designed and built to investigate the effects of thermal cycling on the material properties of GLARE (glass fibre reinforced aluminium). Peltier elements were used to provide external heating and external cooling by inverting the direction of the electrical current. With the same setup, heated GLARE samples can be internally heated using the integrated heater elements and externally cooled using the Peltier elements.

Glass-fibre epoxy composite, GLARE, and heated GLARE samples have been thermal cycled for 4000, 8000 and 12,000 cycles with temperature differences of 120 °C. The interlaminar shear strength (ILSS) increased by 6.9% after 8000 cycles for the glass-fibre epoxy composite material compared to the non-cycled samples. The GLARE samples showed a maximum ILSS increase of 4.2% after 12,000 cycles. However, the heated GLARE samples showed a continuous decrease of the ILSS with a maximum decrease of 7.8% after 12,000 cycles.

1. Introduction

1.1. Integrated electric de-icing

Future aircraft demand state-of-art lightweight and eco-efficient systems and structures. The trend goes towards more electric aircraft to obtain these objectives. Integration of functions in an aircraft part is another way to reduce weight and obtain more efficient performance [27]. A multifunctional material or part can for instance add thermal, electrical or monitoring functions to its conventional structural function.

The thermal function is of particular interest for the leading edges of an aircraft [2,9,17]. Leading edges have to be heated to avoid atmospheric ice accumulation on the surface of the wings. Ice accumulation can alter the shape of the air foil and thus can lead to loss of aerodynamic performance. Conventional systems blow hot air from the engines through a series of ducts to the leading edge to melt the ice away. This however, requires support structures which lead to additional weight.

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1.2. Embedding heater elements in FML

Fibre metal laminates (FMLs), such as GLARE, i.e. glass-fibre reinforced aluminium, are nowadays used on the Airbus A380 [1,31]. The alternating metal and composite lay-up in FML seems ideal for the development of a multifunctional structural skin with embedded heater elements for the application in leading edges. The heater elements are protected from environmental influences by the outer aluminium layer and electrically shielded by surrounding glass-fibre epoxy layers. Numerous studies have been conducted which showed the enhanced material characteristics of GLARE over monolythic aluminium including the improved fatigue and damage tolerance [1]. Furthermore, an outstanding burn-through resistance was revealed and thermal material properties were determined [13,18].

1.3. The effect of thermal cycling on FMLs

Many durability aspects have been investigated for FMLs [33]. Test data on thermal cycling of FML however is limited. Moreover, these tests were not performed on the FM906 high temperature curing epoxy which is currently used in heated GLARE and the number of cycles was limited and stayed below 2000 [7,23]. However, with the assumption that de-icing systems are switched on twice during 20% of all flights this could implicate a total of 36,000 cycles for a regional passenger aircraft with a design life of 90,000 flights. The number of cycles can easily be tenfold this number of cycles when taking into account that the system is generally switched on and off repeatedly during a de-icing scheme. Thus, thermal cycling tests which simulate the de- or anti-icing conditions of heated FMLs are needed to investigate the effects on their material properties. The (local) thermal stresses induced by thermal cycling due to the different thermal expansion coefficients could lead to material cracking and debonding at the interfaces. The thermal loading can also lead to ageing of the glass-fibre epoxy system and thus affect thermal and mechanical properties such as thermal expansion, shear strength, and fracture toughness.

1.4. Thermal cycling developments

Thermal cycling fatigue, i.e. exposing materials and structures to alternating temperatures, has been a research topic for decades [7,10]. That research focused on the effects of thermal cycling on the material characteristics and on the structural integrity of components [16]. Thermal cycling tests with different heating and cooling methods, for different heating and cooling rates and different dwell times were developed [11,22].

Besides structural materials which are used e.g. in aircraft [7,10], thermal fatigue is also a known issue in materials for dental care [11] and electronic parts [22]. The alternating thermal loading of materials used for dental care and the combination (by bonding) of different materials combined with safety issues result in high demands on the material [26] and adhesive properties [14]. In the case of electronic parts, the investigation of thermal fatigue on the local (material) and the global (component) level is relevant [24]. The change of material characteristics is likely to change both the structural integrity and performance of (electronic) parts.

1.5. The proposed setup for (heated) FMLs

To investigate the effect of thermal cycling on (heated) FMLs an experimental setup is required which is reliable and capable to simulate flight conditions. The thermal loading conditions of heated FMLs due to flight conditions can be divided into thermal cycling due to the ascent and descent of aircraft (external cooling and heating) and thermal cycling due to (local) heating of the leading edges by de- and anti-icing measures (external cooling and internal heating).

The novelty of the thermal cycling setup introduced in this article is the ability to perform thermal cycling of materials with and without embedded heater elements. For structural materials the thermal cycling setup provides external cooling and external heating. For multi-functional materials (materials with embedded heater elements), the experimental setup enables thermal cycling tests by providing external cooling and internal heating. In order to simulate flight conditions, the experimental setup can be adopted to provide constant external cooling using the Peltier elements and sequential internal heating using the embedded heater elements. Furthermore, the dwell times at the minimum and maximum temperatures can be adjusted. Dwell times are used to simulate anti-icing conditions as in this case the heater elements are eventually switched on for several minutes contentiously to completely avoid icing.

In this study thermal cycling was performed on glass-fibre epoxy composites, GLARE and heated GLARE (see Fig. 1) and their material properties examined before and after thermal cycling. The test results after the high number of 12,000 thermal cycles, the chosen temperature ranges of 120 °C which simulate de- and anti-icing conditions and the innovation of embedding heater elements in FMLs contribute to understand the effects of thermal cyclic loads on leading edges using heated FMLs.

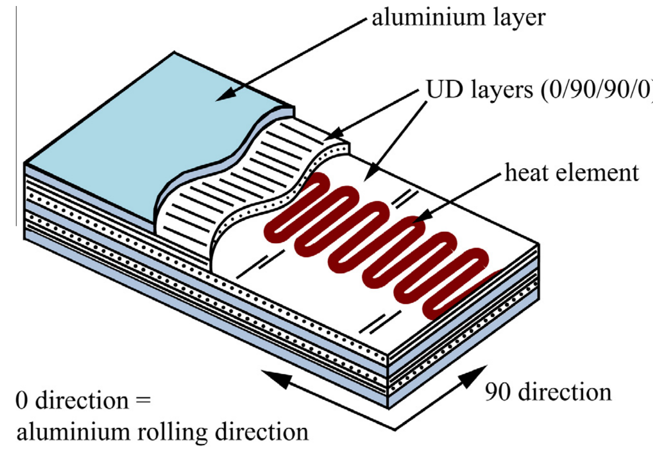

Fig. 1. Schematic lay-up of a heated GLARE laminate.

2. Heated GLARE

2.1. The heated GLARE lay-up

Heated GLARE is a FML with an embedded copper mesh between the unidirectional (UD) prepreg layers [9]. To enhance the de- and anti-icing capabilities of leading edges, the copper mesh is positioned between the UD layers which are directly underneath, i.e. as close as possible to the outer aluminium layer in the heated GLARE laminate. Fig. 1 shows the schematic lay-up of this multi-functional FML. In the conventional GLARE configurations FM94 glass-fibre prepreg is used. The stiffness of this 120 °C curing epoxy system decreases significantly at temperatures beyond 70 °C [13]. In heated GLARE therefore FM906 glass-fibre prepreg is used, which is a 180 °C curing epoxy system with a T_g of 135 °C and estimated maximum service temperature of 120 °C. In combination with aluminium 7475T761 the FM906 is used as high static strength (HSS) GLARE with improved strength and service temperatures over the standard GLARE [21].

Mechanical and thermal stresses are expected to be present in heated FMLs during their service time in leading edges. Thermal residual stresses develop due to different thermal expansion of the individual materials after curing [12]. Moreover, residual stresses can result from forming processes like bending [28]. These stresses are superimposed with the mechanical and thermal service loads which appear at leading edges.

2.2. Thermal loading conditions

Fig. 2 shows the expected thermal loading conditions of heated GLARE laminates which are used as anti- or de-icing devices (light brown beams) and the thermal loading conditions which were realised (red beams) in this article. Furthermore, Fig. 2 depicts the lower and upper limit of the service temperature of the glass-fibre epoxy FM906 and its curing temperature. Moreover, the temperature at which ageing effects and a considerable reduction of the material properties of aluminium are expected are indicated [25,29]. Above approximately 140 °C ageing can cause moderate effect on the mechanical properties of the aluminium after a total exposure time in the order of weeks. Above approximately 200 °C the aluminium stiffness decreases more significantly and ageing happens faster [25,29].