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The applicability of magnesium based Fibre Metal Laminates in aerospace structures

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ABSTRACT

This paper discusses the application of magnesium alloys in Fibre Metal Laminates. The advantage of low density as compared to current light alloys comes along with various disadvantages in mechanical properties. To determine whether this alloy is applicable in a Fibre Metal Laminate configuration for aircraft structures, the effect of the properties on the overall FML behaviour has been addressed. This paper provides an initial evaluation of FMLs based on current magnesium alloys, using knowledge and prediction models developed for current FMLs validated with a limited amount of data obtained from the literature.

1. Introduction

The introduction of the Fibre Metal Laminate (FML) concept in aerospace applications created another mind set among researchers and engineers. The advantages of combining metallic materials with fibre reinforced polymer composites has been widely identified and acknowledged. The concept, initially developed at Delft University of Technology at the beginning of the 1980s [1,2], has been further explored with the application of constituent materials other than the aluminium, aramid and glass fibres used for Arall and Glare. Among others are the combinations of aluminium with carbon fibres (Carall) [3–7] and, for high temperature applications, the combination of titanium and carbon fibres (TiGr) [8,9]. In the quest for structural weight reduction, in addition to the weight reductions achieved so far with the application of Glare, some researchers have initially explored the application of magnesium [10,11].

In general, the development of the various FML concepts has been performed with the following approach: a given combination of constituents has been explored experimentally and from the obtained material properties the question had to be answered where a material with such properties might be applicable. The fact that most FML concepts discussed in the literature so far have not yet been applied in an actual structure, might be attributed to the fact that the obtained properties did not match with the demands of any potential structure.

To develop relevant FML concepts, the potential structural applications should be at least considered to determine the objectives with respect to material performance. In the case of magnesium based laminates for instance, the authors claim to have developed a new range of FMLs. Nevertheless, a potential application has not yet been identified and thus the required material properties for magnesium based FMLs are yet to be determined.

The main question therefore is: what is the potential application of magnesium based FMLs for actual aerospace applications? To which ranges should all the relevant material properties be tailored before it can be concluded that an actual concept has been developed? To initiate such an evaluation, this paper discusses the potential of structural and material properties of magnesium based laminates based on some experimental observations and analytical models.

2. Background

As advantages of the application of magnesium alloys over aluminium alloys, Cortés and Cantwell [11] mention low density and improved electromagnetic shielding capability. Interestingly enough, they also mentioned superior corrosion resistance, which seems to be rather a point of concern for magnesium looking at other studies [12,13]. The latter aspect becomes even more interesting considering the fact that the authors report tests on magnesium laminates with carbon fibres. The issue of galvanic corrosion reported for the combination with aluminium [4] can be considered to be even more significant for magnesium.

Despite the benefits of applying magnesium in FMLs, there are several aspects that require further elaboration before one can state that a new range of magnesium based FMLs has been developed.

With the emphasis being put on the high stiffness advantage of carbon fibre reinforced polymer over monolithic aluminium, the low stiffness of magnesium for structural applications should be properly addressed. It has been reported that Glare has a stiffness that is lower than monolithic aluminium [14–16], which is

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Nomenclature

a	half crack length [mm]
C	constant in Paris crack growth relation
E	elastic tensile modulus [MPa]
G	elastic shear modulus [MPa]
K	stress intensity factor [MPa$\sqrt{}$mm]
K_t	stress concentration factor
N	number of cycles
n	constant in Paris crack growth relation
R	stress ratio (S_{min}/S_{max}) [MPa]
S_a	applied stress amplitude [MPa]
ν	Poisson's ratio
BYS	bearing yield strength [MPa]
CTE	coefficient of Thermal Expansion [1/°C]
CYS	compression Yield Strength [MPa]
MVF	metal volume fraction
SS	shear strength [MPa]
TYS	tensile yield strength [MPa]
UTS	ultimate tensile strength [MPa]

attributed to the lower stiffness of the glass fibre layers. Combining Glare with a monolithic aluminium back-up structure (stringers, clips and frames) could induce unfavourable stress distribution between skin and reinforcing structure. This could in the end result in fatigue problems in the back-up structure, which are not easy to inspect and detect. In Glare structures, this issue can be avoided by using Glare stringers and through careful design of other non-Glare sub-structure elements. However, stiffness values reported by Cortés and Cantwell for magnesium based FMLs will make any design solution impractical. Their glass fibre based FMLs have a modulus of elasticity below 38 GPa and their FMLs based on the high stiffness carbon fibres have a modulus below 48 GPa. For comparison, the cross-ply Glare laminates have a modulus ranging from 49 to 64 GPa, while monolithic aluminium has a modulus of 72.4 GPa.

Other aspects that need to be investigated are the fatigue aspects related to the application of magnesium in FMLs. The concept of FMLs was initially developed to obtain improvements in fatigue performance over monolithic metals. Additional benefits, such as impact resistance, were discovered later in the development of the FML concept.

Looking at the fatigue properties of magnesium reported in the literature, there are some points of concern. First, although Cortés and Cantwell report an increase of fatigue crack propagation life in magnesium based FMLs over monolithic magnesium, one has to keep in mind that the reported fatigue lives are lower than those of monolithic aluminium and are thus unacceptable for current structural applications.

Beside crack growth, initiation of fatigue cracks needs further investigation. It is known that the initiation of cracks is attributed to the actual stress cycle in the metal layer of the FML [15]. Similar stress cycle and stress concentration, defined in peak and nominal stresses in the metal layer, gives similar initiation behaviour.

The stress cycle in the metal layer is influenced by the stiffness difference between the metal and fibre layers, which might be favourable for magnesium because of its low stiffness. The residual stresses induced by the curing process must be added to that. Although the difference between the CTE of aluminium and magnesium is limited, these curing stresses should certainly be considered when applying thermoplastic matrix systems in the FML. The higher required curing temperatures raise the residual stresses, resulting in a significant reduction of initiation life. This becomes even more important, when one considers the full operational temperature range of an aircraft. Residual stresses at −50 °C when curing at 185 °C should be considered to be extremely high.

To increase the crack growth performance of magnesium based FMLs, an attempt can be made to increase the delamination resistance of the interfaces. Increasing the delamination resistance gives smaller delamination areas, which are known to increase the bridging efficiency and thus reduce the crack growth. However, that can only be done to a limited extent, because insufficient delamination could increase the fibre stresses leading to early fibre failure. Based on the experience with Arall [17], it can be concluded that fibre failure must be avoided at any time during fatigue crack growth, because it significantly reduces the bridging efficiency.

Another measure related to delamination that could be considered is the reduction of load transferred over one interface by increasing the amount of interfaces. This could be achieved by reducing the thickness of the magnesium layers, or by applying more fibre layers in-between the magnesium layers. Because the production of very thin magnesium layers is known to be difficult, the latter solution might be preferable.

Some authors claim that the application of thermoplastic systems instead of the thermoset significantly increase the interlaminar fracture toughness. The question is, however, whether this also translates in higher delamination resistance during cyclic loading. In addition, one has to consider the increase in load transfer over an interface as result of the residual stresses due to higher curing temperatures.

3. Potential FML applications and design criteria

In order to determine the value of applying magnesium in the FML concept, the potential (range of) applications have to be identified first. Subsequently, the design criteria must be identified following from these applications. From there, the required properties can be derived, which can be translated in the proper development of the magnesium based FML concept. Only after taking these steps, it is possible to conclude whether or not a new range of possible FMLs has been developed.

The success of the FML concept in general and Glare in particular is that they perfectly fit in the damage tolerance philosophy exploited in current aircraft design. The laminated material inherently provides a second load path, making it a damage tolerant material [18].

As a result, the current primary structural applications are mainly the fuselage skin structures, in particular the upper section prone to high tensile fatigue loading. In addition, the D-noses of the horizontal and vertical tail planes are being made of Glare, because of its excellent impact resistance.

Based on the past success of FMLs in terms of fatigue and damage tolerant behaviour and using the current static strength properties achievable with FMLs, the potential of magnesium based FMLs for applications demanding these properties will be evaluated in the remainder of this paper.

4. Brief review of literature data

To discuss the potential of the magnesium based laminates, some experimental data is available in the literature. However, to compare with existing FMLs in a reliable way, analytical evaluation is inevitable. For this purpose, the developed prediction models