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Fracture properties of a fiber-metal laminates based on magnesium alloy

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Fiber-metal laminates (FMLs) are high performance laminated structures based on stacked arrangements of composite material and aluminum alloy. Currently, a glass fiber reinforced epoxy/aluminum alloy FML (GLARE) is being considered for use in the manufacture of the upper fuselage of the A380 Airbus aircraft [1]. Previous work on FMLs has shown that they combine the excellent durability and machinability common to many metals with the superior fatigue and fracture properties offered by many fiber-reinforced composites [2–4]. Krishnakumar [2] tested a Kevlar fiber FML (ARALL) and showed that its ultimate tensile strength is considerably greater than that of a conventional aluminum alloy. Vogelsang [3] conducted tension-tension fatigue tests on a number of FML systems as well as a plain aluminum alloy and showed that crack growth rates in the former were significantly less than those in the plain aluminum alloy.

Several workers have investigated the impact response of aerospace-grade fiber-metal laminates [5, 6]. Vlot *et al.* [5] conducted low and high velocity impact tests on a GLARE system, a plain aluminum alloy and a carbon fiber reinforced thermoplastic. Their results showed that the FML offered the highest damage threshold energy of all the systems considered.

The aim of the present work is to investigate the fracture properties of a novel fiber-metal laminate based on a lightweight magnesium alloy and a carbon fiber reinforced plastic. Magnesium alloys offer a number of advantages over many metals including their low density (thirty percent lower than an aluminum alloy), their superior corrosion resistance and their excellent electromagnetic shielding ability. Currently, magnesium alloys are being used in the automotive industry in the manufacture of transmission casings and in the aerospace industry for the manufacture of gearboxes and other lightweight components.

The fiber-metal laminates examined in this study were based on 0.5 mm thick magnesium alloy sheets (AZ31 alloy from Advance Metals International Ltd.) and a woven carbon fiber reinforced toughened epoxy (Stesapreg EP121-C15-53 from Stesalit Ltd, Switzerland). The composite and metal plies were placed in a picture frame mold with dimensions 240 × 200 mm and cured for 4 h at 125 °C. All of the laminates tested in this research project were based on a 2/1 configuration (two magnesium alloy skins either side of a carbon fiber reinforced epoxy core). Table I summarizes the stacking configurations investigated in this study.

The composite volume fraction within the FMLs was varied by increasing the number of composite plies between the two outermost magnesium alloy skins from two to eight. The tensile properties of the FMLs and the magnesium alloy were evaluated using 20 mm wide rectangular samples at a crosshead displacement rate of 2 mm/min. The initial strain history in each sample was recorded using a clip-on extensometer fixed to the specimen edge. The extensometer was incapable of measuring large strains. In such cases, the crosshead displacement was normalized by the length of the working section to yield a nominal strain (this was only undertaken when a complete stress-strain curve was required).

The energy-absorbing properties of the fiber-metal laminates were evaluated through a series of single edge notch bend (SENB) tests on specimens with dimensions 100 × 18 mm × thickness. Prior to testing, a 9 mm long pre-crack was introduced at the mid-span. The pre-crack was sharpened by swiping a sharp razor blade along the tip of the stress concentration. The SENB specimens were positioned on two simple supports positioned 72 mm apart and loaded at a crosshead displacement rate of 5 mm/min. The work of fracture was then determined by dividing the area (energy) under the load-displacement curve by the cross-sectional area of the fractured ligament.

Fig. 1 shows typical stress-strain (nominal) curves for the three FMLs and the plain magnesium alloy. The stress-strain curve for the plain magnesium alloy indicates that although its tensile strength is below that of the FMLs, it does exhibit quite a high degree of ductility beyond the elastic limit. The stress-strain curves for all of the FMLs exhibited an almost linear response up to maximum stress at which point the composite layers fractured in a brittle manner. An examination

TABLE I Summary of the carbon/epoxy-based FMLs examined in this study

Laminate	Stacking configuration	Composite volume fraction	Laminate thickness (mm)
1	Mg, CE_2, Mg	0.36	1.63
2	Mg, CE_4, Mg	0.57	2.18
3	Mg, CE_8, Mg	0.67	3.06

Mg = ply of magnesium alloy, CE = ply of carbon/epoxy material.

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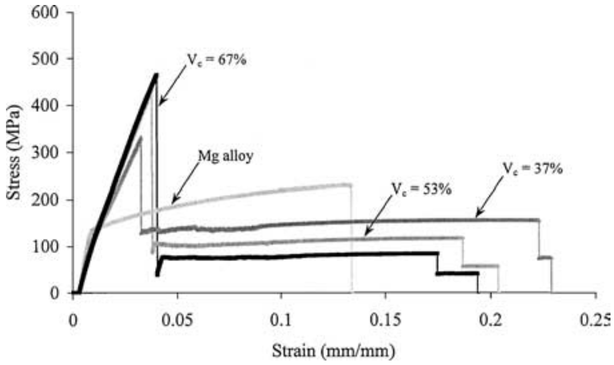

Figure 1 Typical stress-strain curves following tensile tests on three magnesium/carbon fiber epoxy/FMLs.

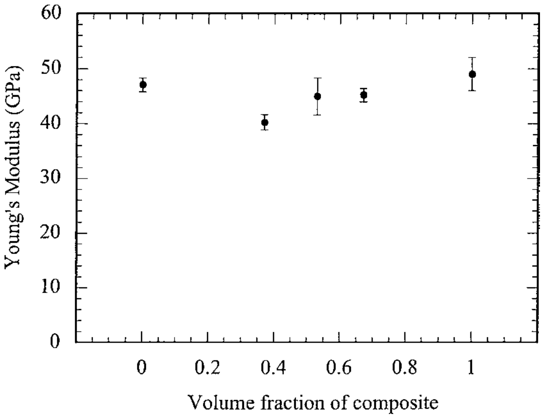

Figure 2 The variation of the tensile modulus of the magnesium FMLs with composite volume fraction.

of the samples indicated that a crack had traversed the composite layer in all specimens before propagating vertically along the composite-metal interface. Further loading of these samples resulted in failure of the magnesium alloy plies at relatively high strains.

Fig. 2 shows the variation of the tensile modulus of these magnesium-based FMLs with increasing volume fraction of composite. From the data, it is clear that the tensile modulus of these systems remains roughly constant with the addition of the carbon fiber/epoxy. This is not surprising since the Young's moduli of the plain composite and the magnesium alloy are very similar. The variation of the tensile strength of the FMLs with increasing volume fraction of composite is shown in Fig. 3. Here, increasing the amount of carbon fiber/epoxy in the laminates has a positive effect with the strength increasing continuously with increasing V_f. The solid line in the figure represents the predictions of a rule of mixtures approach, clearly, agreement with the experimental data is very good. Fig. 4 compares the specific tensile strength (tensile strength normalized by density) of the magnesium-based FMLs with a similar system based on a 2024-T0 aluminum alloy [7]. The figure shows that the specific tensile strength of the magnesium FML is slightly higher than that associated with its aluminum-based counterpart. It is clear, however, the higher strength grades of aluminum alloy should offer a superior performance to that observed here.

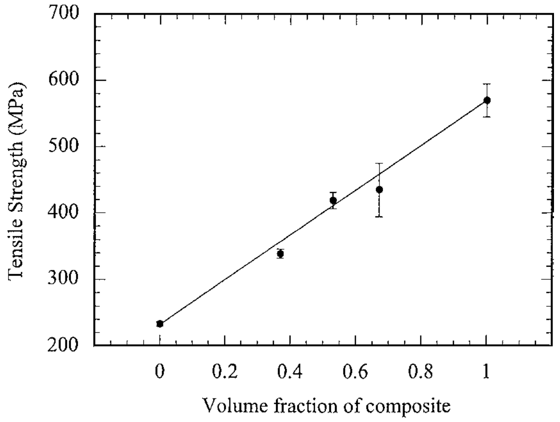

Figure 3 The variation of the tensile strength of the magnesium FMLs with composite volume fraction. The solid line represents the predictions of a rule of mixtures approach.

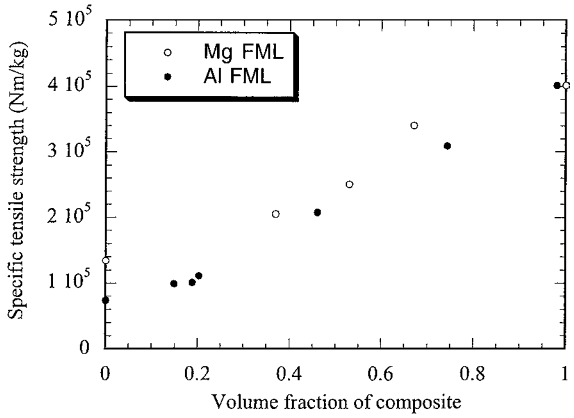

Figure 4 A comparison of the specific tensile strength of the magnesium FMLs investigated in this research program and an aluminum FML based on the same carbon fiber reinforced epoxy [7].

The effect of composite volume fraction on the fracture properties of the FMLs was investigated by conducting single edge notch bend tests at a crosshead displacement rate of 5 mm/min. Crack propagation in the FML samples occurred in a stable fashion with the load steadily decreasing with increasing crack length. Fig. 5 shows the variation of the work of fracture, W_f, with composite volume fraction. Also included in the figure are the values for the plain magnesium alloy and the carbon fiber reinforced epoxy. The figure clearly shows that the work of fracture of the magnesium alloy

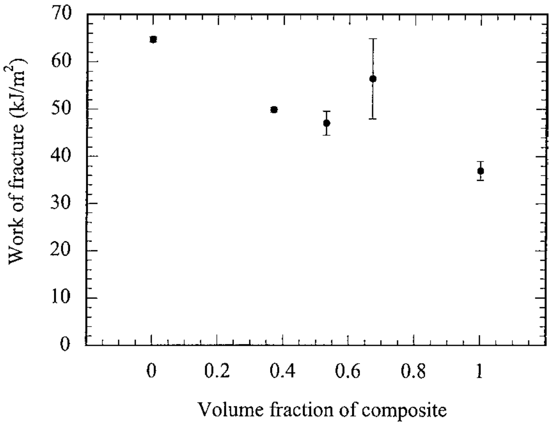

Figure 5 The variation of the work of fracture of the magnesium FMLs with composite volume fraction.

is significantly higher than that of the plain composite. Increasing the amount of composite in the FML therefore has the effect of reducing the value of W_f. The average value for the system with a composite volume fraction of 67% is clearly higher than that predicted by a simple rule of mixtures approach. An examination of the sample indicated that it had failed in a similar mode to that observed in the other samples and the reason for this slightly anomalous result is not clear. The specific work of fracture values (W_f normalized by density) of these FMLs are lower than those reported for an aluminum alloy system (by up to twenty-five percent) [7] due to the lower toughness characteristics of the magnesium alloy. However, differences in the specific work of fracture are less than ten percent in the system based on the highest volume fraction of composite.

A new type of fiber-metal laminate system has been developed and investigated. Tensile tests have shown that the specific tensile strength of these novel FMLs is higher than that of corresponding systems based in a 2024-T0 aluminum alloy. Tests have also shown that the elastic modulus and work of fracture properties of these hybrid systems are lower than those offered by an aluminum-based system although these differences can be minimized through the appropriate choice of composite volume fraction.

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