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LETTER

Interfacial fracture properties of environmentally friendly hybrid systems

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Hybrid systems consist of alternating layers of metal and fiber-reinforced polymer matrix composites. These systems also referred as composite metal laminates (CML) exhibit excellent resistance to fatigue and impact loading as well as superior specific stiffness and strength [1]. In addition, the residual strength of cracked CMLs has been shown to be greater than that of the plain metal counterpart as a result of crack bridging between the composite and metal constituents [2–4]. Traditionally, CMLs are based on thermosetting polymer matrices which normally exhibit a brittle deformation behavior and are associated with long manufacturing cycles. In contrast, thermoplastic-based CMLs offer significant advantages, including shorter processing times, high fracture toughness and the possibility of post-impact repair. However, one of the limiting factors for the development of these CMLs is the reduced availability of engineering knowledge related to their fracture mechanisms since laminate properties basically depend on the bi-material interfacial bond strength along with the matrix and reinforcing agent properties [5]. Reyes and Cantwell [6–9] have reported excellent mechanical and impact properties for polypropylene-based CMLs compared to monolithic aluminum. Here, an amorphous chromate coating surface treatment applied to the aluminum substrates combined with a layer of maleic anhydride modified polypropylene were used to achieve an excellent level of adhesion along the bi-material interface. However, the use of chrome VI that is utilized in such surface treatments has been restricted by the control of major accident hazards (COMAH) as a result of its harmful environmental impact. Therefore, this letter presents the results on the interfacial fracture properties of lightweight composite-metal hybrid systems based on thermoplastic composite materials and aluminum alloy by applying environmentally friendly (non-chromate) surface treatments to the metal substrates. In addition, the affect of varying the number of modified polypropylene interlayers is explored.

The hybrid systems were based on aluminum alloy 2024-T3 and polypropylene (PP) based composites (Curv® and Twintex®). The first composite is a self-reinforced composite where PP fibers with a high degree of molecular orientation are embedded in a PP matrix. The second composite is a woven glass fiber PP in a commingled form. In order to promote a good level of adhesion between the dissimilar materials, a newly developed environmentally friendly surface treatment was applied to the metal substrates (CC-300 chrome free seal from Sanchem Inc.) prior laminating. In order to optimize the level of adhesion between the composite and aluminum alloy, a 40 g/m^2 film of modified polypropylene (XAF from Collano Xiro AG) was incorporated at the interface during the manufacturing procedure. Laminates of dimensions 240 × 200 mm were stacked in a picture frame mold. The mold was then placed in an air-circulating oven and heated to 170°C. Following this, the mold was removed from the oven and stamped in a cold press to ensure a low degree of crystallinity in the polypropylene matrix [10].

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Single cantilever beam tests were performed on a screw-driven Instron 4469 universal testing machine as shown in Fig. 1. The specimens were clamped at one end of a steel fixture and then loaded at the opposite end at a crosshead displacement rate of 1 mm/min forcing a crack to propagate from the tip of the pre-crack. The mixed mode interfacial fracture energy was determined by a compliance calibration method. This technique assumes a compliance vs. crack length relationship of the form:

$$C = C_0 + ma \tag{1}$$

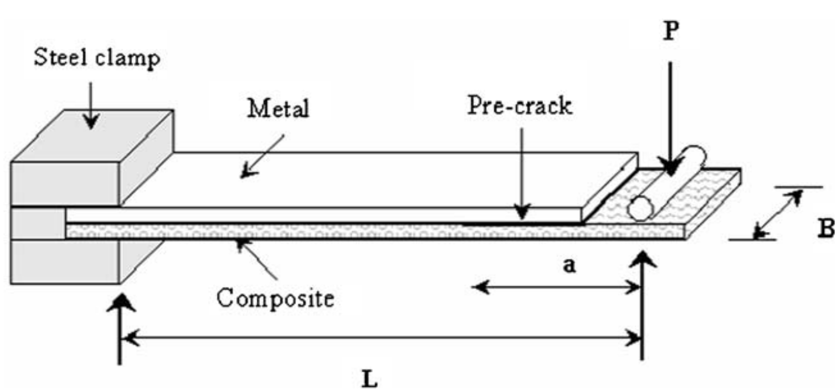
where C_0 and m are experimentally determined constants. Here, a graph was plotted between compliance vs. the cube of crack length and m was determined by measuring the slope of the graph. The mixed-mode interfacial fracture energy was then determined using:

$$G_{I/IIc} = \frac{3P^2ma^2}{2B} \tag{2}$$

Typical load-displacement curves for the aluminum (CC-300)/Curv system using 1 and 2 layers of XAF are shown in Fig. 2. Here, the system with one layer of XAF exhibits non-linear behavior in the initial part of curve. This is believed to be as a result of the presence of small amounts of plastic deformation in the metallic layer. Continued loading of the specimen resulted in an increase of the load reaching values close to 130 N. At this point, a change in the locus of the crack from interfacial to interlaminar was evident in the hybrid system. Following this, the crack propagated within the self-reinforced composite material in a stable manner without any sudden drop in the load. Increasing the number of the adhesive layers resulted in a steeper linear elastic behavior up to approximately 80 N. Plastic deformation of the interfacial layer was observed up to a load of approximately 100 N. Following this, a change in the mode of crack propagation was observed once again. Continued loading resulted in the crack propagating in a stable manner plateauing at values close to 140 N.

Figure 3 shows typical load-displacement curves for the aluminum (CC-300)/Twintex system after SCB testing. From the figure it is clear that both curves show an initial linear response until a load of approximately 170 N and 220 N was reached for the systems with one or two layers, respectively. Continued loading resulted in inelastic deformation followed by stable crack propagation. It is interesting to note that the system with two layers exhibit

Fig. 1 Schematic illustration of the SCB test geometry



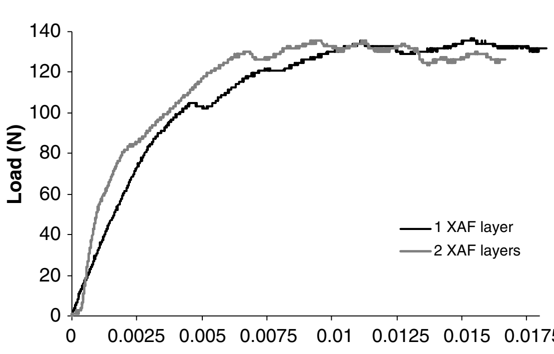


Fig. 2 Typical load displacement curves of CC-300 treated aluminum/Curv samples following SCB testing at 1 mm/min

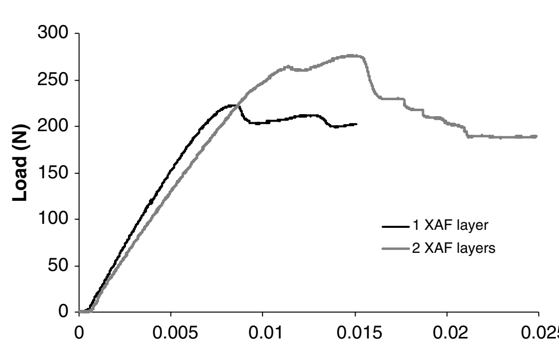


Fig. 3 Typical load displacement curve of CC-300 treated aluminum/Twintex samples following SCB testing at 1 mm/min

higher load bearing capabilities compared with the system with only one layer of XAF. This clearly suggests that the thickness of the interlaminar adhesive plays an important role in the interfacial fracture properties of these hybrid systems. In order to get a better understanding of the interfacial fracture mechanisms, a number of failed specimens were examined under an optical microscope. Figure 4 shows the fracture surfaces of the system consisting of aluminum (CC-300)/Twintex with two layers of XAF. Here, crack propagation is from right to left. A closer examination of the metallic substrate reveals significant amounts of residual self-reinforced PP as well as small amounts of the XAF adhesive. This suggests that crack propagated initially in an interfacial mode followed by an interlaminar mode indicating that the interlaminar fracture properties of the plain self-reinforced PP are lower than the interfacial fracture properties of the hybrid system. Furthermore, this suggests that the combination of environmentally friendly surface treatments and XAF promotes a good level of adhesion between aluminum and thermoplastic composites.

The Load displacement plot was used to calculate the mixed-mode interfacial fracture energy using Eq. 2. Here, the value of the constant m was calculated from the slope of the plot of C vs. a^3 were the data laid in a reasonably straight line and a linear fit to the data yielded the value for the constant. Following this, the interfacial fracture energy was then plotted against crack length. A typical resistance curve for the aluminum/Curv system with two layers of XAF is shown in Fig. 5. From the figure, it is clear that the interfacial fracture energy rises rapidly as crack length increases reaching values of approximately 1800 J/m^2.

An examination of a number of specimens during testing indicated that the rising R-curve was associated with the development of crazing in the wake of the crack and the presence of energy absorbing mechanisms linked to interlaminar types of fracture.

Finally, a summary of the interfacial fracture properties of the hybrid systems studied in this project is shown in Fig. 6. Clearly, the Curv based systems exhibited very similar values with one and two layers of XAF as a result of the crack propagating in an interlaminar manner. In contrast, the effect of number of XAF layers was more pronounced on the Twintex based hybrid systems. Here, using 2 layers of XAF resulted in an increase from approximately 2000 J/m^2 to approximately 2800 J/m^2 suggesting that an excellent level of adhesion between the thermoplastic composites and the metal substrate can be achieved.

In this letter, the interfacial fracture properties of a number of environmentally friendly thermoplastic composite metal hybrid systems have been evaluated. Here, the interfacial fracture properties of the self-reinforced composite based hybrid systems were found to be dominated by

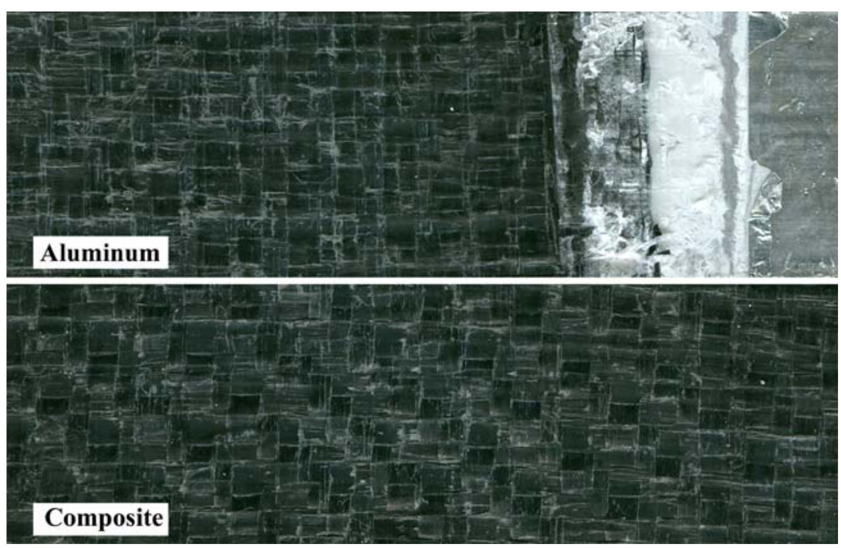


Fig. 4 Low magnification optical micrographs of fracture surfaces of a CC-300 treated aluminum/Curv sample after SCB testing

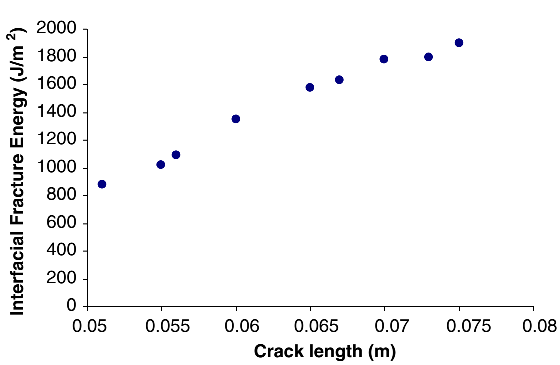


Fig. 5 Typical R curve for Al/XAF(2)/Curv hybrid system after SCB testing at 1 mm/min

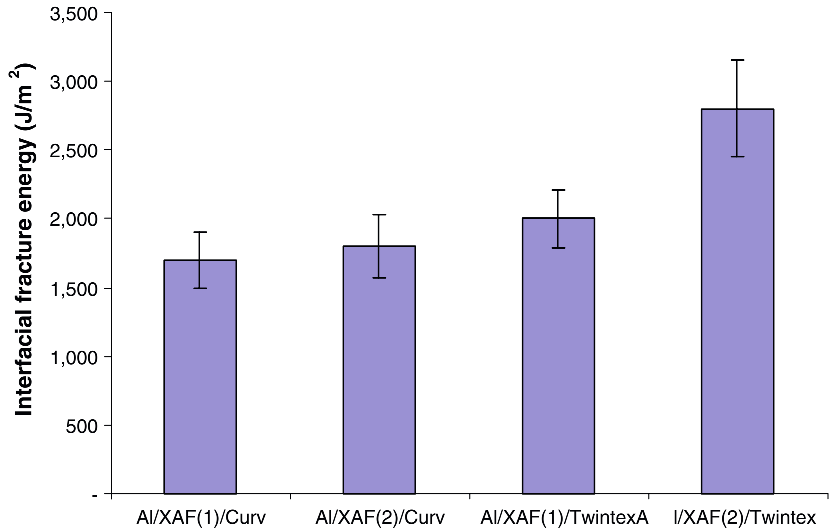


Fig. 6 Summary of interfacial fracture properties of hybrid systems tested under SCB loading conditions

the interlaminar fracture properties of the bulk composite. In contrast, the Twintex based systems with two layers of XAF exhibited higher values of interfacial fracture energy. Finally, it has been shown that a good level of adhesion between the thermoplastic composites and the metallic materials can be achieved by applying a non-chromate surface treatment to the aluminum substrates. This opens up a new window of opportunities for the use of these hybrid systems in applications that demand environmentally friendly materials with excellent mechanical properties.

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