mercial buildings. The market growth prospects are significant, since not only new-construction but also the upgrade of existing systems are involved. Advanced low FST composite materials for aircraft, principally based on phenolic or thermoplastic resins, that reportedly conform to the proposed FAA 1990 rule and the *Airbus Industries ATS 1000.001* specification have been introduced by a number of companies. Composite suppliers are also quite active in the development of FST aircraft floor panels. *Hexcel* and *Quadrax* have teamed to produce a thermoplastic sandwich panel to fulfill this requirement.

Although the most widely known fire-suppression programs are directed at aircraft interiors, potential applications include most areas in marine surface ships above the water line (*e.g.* deck houses, joiner panels, ducts, and armor), aircraft engine cowlings, and burn through barriers in air conditioning ducts, elevator shafts, office partitions, hospital walls, utility control rooms, and emergency shelters. The United States Navy has several development programs evaluating the applicability of advanced composites on surface-ships and submarines. Weight reduction and fire properties are the main parameters of interest. An example of a commercial realization of the composite industry's *R&D* efforts is a new lightweight low FST composite system recently offered by *Ciba-Geigy*. The material is manufactured as a sandwich structure and capable of O.S.U. values of 10/10. It meets the toxicity requirements of *ATS 100* and U.S. domestic specifications. Utilizing specific constructions, it can provide 1-h burn through protection in a 1093° (2000°F) direct flame. Large-scale component tests have been successfully conducted in several U.S. Navy ship applications including fire main pipes and air conditioning ducts.

Conclusion

Advanced polymer composites have been successfully used in a wide variety of commercial applications. Carbon, glass, and organic fibers combined with thermoset and/or thermoplastic matrix resins have provided performance, weight, and cost advantages over traditional materials. Future use will be influenced by advanced polymer technology advancements and reductions in fabrication and tooling costs.

The author would like to express his appreciation to *Richard Heitkamp* and *Tom Jonas, Ciba-Geigy Composite Products*, Anaheim, California, for their technical assistance in preparing this paper.

[1] C.A. May, Ed., 'Resins for Aerospace', ACS Symposium Series, No. 132, American Chemical Society, Washington, DC, 1980.
[2] G. Pritchard, Ed., 'Developments in Reinforced Plastics-1', Resin Matrix Aspects, Applied Science Publishers Ltd., London, 1980.

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A Study on the Toughening of Polymer Matrix Composites by Interphase Modification

Andrea Pavan*

Introduction

While the combination of different materials to produce a composite with new or enhanced properties is an established concept, the interaction of the constituent phases along their interfaces remains of some concern.

It is generally assumed that a certain degree of adhesion between matrix and inclusion is necessary to provide some degree of collaboration; but it has also been demonstrated that too strong an interfacial bond may impair some properties of the overall composite material, especially toughness. For optimum performance, the magnitude of the interfacial bond strength should be adjusted for each specific application [1].

Modification of the interface by surface treatment (of the inclusions) to adjust the interfacial bond must take into consideration surface morphology and energetics.

Interfaces and Interphases

In discussing the interfaces between different composite constituents, the fact must not be ignored that the actual contact surface is not a geometrically clear-cut surface, nor are the properties of the two components close to the interface the same as they are in the bulk: all solid phases have skins, whose characteristics are determined by the conditions prevailing at the boundary between the phases in the course of composite preparation and processing.

Conceptually, we are brought to consider the existence of interphase regions of some finite thickness, with variable composition and microstructure. The properties and extent of these regions can have pronounced influence on the properties of the composite material, especially in terms of mechanical strength and chemical and thermal durability.

Having recognized this fact, considerable research effort has lately been devoted, on the one hand, to exploit the possibilities of altering the composition and structure of the interphase, so as to improve composite performance, and, on the other, to characterize and understand the effect of the interphases on the overall properties of the composite material. It is believed that, if accurate predictive models of interphase behaviour can be developed and integrated into a model of composite performance, it may be possible to consider the interphase a composite variable that can itself be varied in a rational manner to optimize composite performance [2].

From Interphases to Interlayers: Some Recent Experimental Achievements

Since control of the interphases, which form spontaneously, *in situ*, during composite preparation, may be a rather difficult task, an obvious alternative is the introduction of relatively thick interlayers, encapsulating the particulate or fibrous inclusions. It is felt that the structure, properties, and thickness of a relatively thick third phase can be more easily predetermined and tailor-made.

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The idea of coating the surface of hard inclusions (particulate or fibrous) with a layer of soft material, *e.g.* an elastomer, was explored, both experimentally and theoretically, as early on as the seventies (examples are quoted in [3]). Although both theoretical predictions and experimental confirmation were promising, this technology remained substantially unexploited.

More recently, interest and significant research in this field has resumed and is on the increase. *McGarry* [4] reports new progress on methods to deposit thin films of elastomer on the surface of glass microspheres [5], and of glass [6] or graphite [7] fibres, both continuous and chopped. This rubber modification of the reinforcement was successful in improving several mechanical properties (impact and fatigue resistance, interlaminar shear strength, resistance to impact damage) in epoxy as well as in thermoplastic polymer matrices.

An important factor that has not generally been extensively studied with regard to the overall properties of the composite is the thickness of the elastomeric interlayer.

This problem has been addressed by *Gerard* and coworkers [8] [9] who used the approach of *Riess et al.* [10] to place an elastomeric block-copolymer adduct around carbon fibres and glass beads. The fracture toughness of the resulting epoxy-based composites was improved, showing a maximum for a given optimum interlayer thickness.

Theoretical Developments

Many models have been developed to explain the mechanical behaviour of composite materials. Most of them have the common characteristic that they consider the matrix-inclusion boundary as a perfect geometrical surface. The problem of modelling the complex interphase in composites has been addressed by only a few authors. Two approaches are used. In the first, the interphase is considered as a third, intermediate phase having properties halfway between those of the two constituent materials (as, for example, in [11]), whereas, in the second, improved model, the interphase material is assumed as presenting properties that vary continuously between the inclusion and the bulk matrix [12].

The effect of an interlayer of finite thickness with independent properties has also been studied by some researchers, with various limitations (a short review is given in [13]). This author and coworkers have considered the case of a composite material made of a glassy thermoplastic matrix, embedding spherical particles with a hard core covered by a rubbery shell. The micromechanical analysis of that single-particle model [13] was originally aimed at assessing the efficiency of such a particle structure in promoting plastic-yielding (either distortional or dilatational, alias shear-yielding or crazing), which is a prerequisite for toughening. The model has now been further developed to investigate the effect of varying the applied triaxial stress-state, the effect of varying the inter-particle distance between two adjacent particles, and the interaction between unlike particles (hybrid composites). Preliminary comparison of the results of the theoretical analysis with available experimental data appears satisfactory.

Extension of the model to the (more simple) two-dimensional case should enable us to study similar effects in the case of continuous fiber reinforcement.

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