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Recent Advances in Composite Science

One of the major drawbacks to the widespread use of composite materials is our inability to predict their failure modes based on fundamental physics and mechanics. This is especially true for the newer forms—ceramic and metal matrix composites—but also for the more conventional resin matrix materials, such as graphite–epoxy, and also carbon–carbon. Despite our ability to detect the origins of the failures at the constituent material level, scientific treatment with regard to analysis is lacking and empirical methods, including massive experimental programs, dominate design practice. Among the major concerns in a more realistic and rigorous formulation is the effect of interfacial behaviour on the failure response of the composites. This point is quite obvious for the more advanced materials, but transverse failures in graphite–epoxy often initiate at the interface. Even though strong bonding is developed, the inherent characteristics of the interface(s)/interphase region are critical to our understanding of the failure mechanisms. Only by incorporating true mechanistic modeling at the constituent material or micromechanical domain will the design of composites be convincing and lead to higher confidence among the potential users. The dominating influence of the interface(s) is but one of the topics treated in depth in this volume.

Another weakness in composite technology is the inability to interrogate the "health" of a composite structure in a nondestructive manner, in particular, at the constituent material level. Nondestructive evaluation (NDE) has become an integral part of composites research because it affords the possibility to determine local or bulk material properties at various states during the life of a component. Some promising new research in this area is also presented in this issue. Important uses of NDE technology and research in composites involve the determination of failure mechanisms within the composite and, in particular, in the constituents and their interfaces, such as debond opening with friction, and other forms of damage that emanate from the interfaces. This capability is especially necessary in the studies of ceramic and metal matrix composites which have characteristically weak interfaces and multiple interphase regions. Another important use for these methods is in the determination of the elastic properties of the interphase regions themselves. The application of combined methods, such as shear back reflectivity and acoustic microscopy, can be used to great advantage in assessing the character of complex failure modes, which involve more than one type of damage, i.e., fibre breaks plus interfacial debonding.

A third topic currently of great interest and importance is the area of process modeling and new methods of processing which reduce the harmful effects of the harsh environment in present-day process methods on the material itself. While mechanics allows the determination of the ideal properties of a composite, it is processing that represents the art of the possible. Typically, models contain simplifying assumptions which often limit their ability to provide useful insights to the processing community. For example, will a uniform fibre spacing result in a sufficient improvement in composite properties to justify the effort and expense required to achieve it? Or, what is the optimum interface attainable with existing fibre coating technologies and what improvements have the greatest payoff? To realize their full potential, models must "close the loop" between composite processing and composite properties. Residual stresses, initial damage states, and unwanted "springback" deformations, which presently require extensive and expensive retooling efforts are all features of current processing techniques. Several papers in this volume address some of these concerns.

The importance of quality processing and accurate modeling of elastic stress fields are highlighted in the first two papers by Pagano, where composites with controlled fibre spacing are used to query our ability to predict fracture modes within the constituents of a brittle matrix composite under axial loading. In the first paper, a coated-fibre composite is considered, while an uncoated-fibre composite is treated in the second paper. Their failure modes are drastically different as the former fails in a "graceful" manner compared to the latter, which fails in a brittle manner, although the failure process itself is somewhat more complex than that usually assumed in the field of ceramic composite technology. Some new ideas are introduced in these works that examine initial damage development and growth, matrix crack initiation and spacing as a function of applied stress and residual stress, the formation of carbon "mountains" as matrix cracks develop and approach the interfacial region, and ultimate composite fracture. The ultimate failure modes are seen to correlate with scale parameters which are on the order of inherent fibre flaws although the mechanisms are different, one controlled by fibre stress intensification, the other by a fraction criterion. Such detailed evaluation of model quality would not be possible without the use of well-made composites.

The next paper, by Majumdar, Matikas, and Miracle, provides a very detailed examination of the fracture process of fibre fragmentation in a metal-matrix composite. The work features careful experiments on various samples of controlled geometry, such as single fibre and multiple fibre composites. The authors use this information to provide an assessment of the consequences of Curtin's failure model, which is based on Weibull statistics and a simplified representation of the microstress fields. SBR ultrasonics and examination of matrix slip bands are used to question conventional wisdom regarding correlation of fibre fractures and to demonstrate the profound effect of matrix plasticity on this process. Other existing models are used to explain some unexpected features, such as the very high average interfacial shear stress compared to that present in a pushout test. The techniques employed here can also be effective in the study of polymer matrix composites.

The paper by Rokhlin and Huang "Micromechanical analysis and ultrasonic characterization of interphases and interphasial damage in high temperature composites" introduces an inverse method for determination of the interphase elastic moduli from ultrasonically measured composite moduli. The generalized self-consistent model is developed for multiphase composites and used for inverse determination of the effective interphases moduli. It is shown that ultrasonic measurements may be used to determine the static composite moduli which serve as input data in the inversion process. The applicability of the method is demonstrated for various SiC fibre composite systems. Examples of interphase damage characterization are given.

The next paper, by Potel, Chotard, de Belleval, and Benzeggagh, shows the potential of ultrasonic techniques to characterize the evolution of damage in composites in a nondestructive way. Ultrasonic mapping at various depths of a composite plate subjected to impact damage was correlated by destructive tests. A model for ultrasonic propagation in layered media was developed to determine optimum experimental parameters. The model was also used to interpret the experimental results for evaluation of damage in carbon/epoxy composites.

Ultrasonic methods are effective in determining the composite's elastic constants. However, the reconstruction of elastic constants from ultrasonic data is a complex nonlinear problem. The paper by Balasubramaniam and Rao introduces the new idea of using genetic algorithms to solve this problem. The authors used computer simulated ultrasonic data to demonstrate that genetic algorithms can successfully perform reliable reconstruction of the stiffness matrix of a composite.

An important issue affecting the behaviour of polymer matrix composites is the compatibility or adhesion between the fibres and matrix. This adhesion is often developed by the use of sizing or interphase regions. The paper by Iroh and Wood addresses the issue of tailoring the interphase properties of a polymer matrix composite through an electrochemical process. In this work, polypyrrole interphases are introduced as surface coatings on the (carbon) fibres by an electrochemical process. Fibre surface free engery and morphology measurements were taken, and significant improvement over commercial fibres was displayed.

The paper by Sharma and Amateau presents a study of microstructural changes in ceramic composite laminates during the fabrication process. The development of residual stresses, which were confirmed by X-ray diffraction, and stress driven reactions were found to be responsible for the observed microstructural variations in the composites. Knowledge of such properties is required to optimize the design and fabrication of the composites.

The editors feel that significant progress in all three technological areas—micromechanical failure modeling, nondestructive composite material evaluation, and process modeling—have resulted from the papers published in this special volume. We wish to extend our thanks to the authors and reviewers for their fine work and to David Hui for his encouragement, guidance, and support.

Theodeore E. Matikas
and
Nicholas J. Pagano