Designing Interfaces

James A. Cornie, Guest Editor

During the 20 years I have been working in the field of metal matrix composites, I have always been drawn to the study of interfaces. Any problems the materials researcher or developer encounters will eventually be tied to some issue involving the interface. The interface controls the *in-situ* fiber strength and hence the axial strength of the composite. The transverse strength of composites is also controlled directly by the strength of the interface. It follows that in order to optimize a fiber/matrix reinforcement system, one must also optimize the interface. It is no accident, then, that so soon after the two excellent issues on interfaces edited by D. Wolf and S. Yip (*MRS Bulletin*, September and October 1990), we launch into the subject again. This time, we approach the interface from the point of view of integrating the fields of materials science and engineering, i.e., integrating the structure-processing-properties-materials synthesis relationships.

The concept of interface design is relatively new. Until recently, we simply controlled damage and limited fiber degradation by controlling processing variables, and contented ourselves with what nature allowed. For the most demanding applications, nature was not permitting reliable structures.

Our emphasis in this issue of the *MRS Bulletin* is the development of the skills and strategies to design interfaces to a specific application. In the future, we will be asking materials to perform structurally at temperatures approaching 3000°C in some propulsion applications. The success of such applications will depend on how well we design the interfaces.

The lead article, "Designing Interfaces in Inorganic Matrix Composites" by J. Cornie, A. Argon, and V. Gupta, explores the strategy involved in designing composite materials. We see that for continuously reinforced composites, a good interface is not necessarily a strong interface. Cook and Gordon[1] showed that toughness in bi-material structures could be increased by delamination events. In other words, if the interface strength is low enough to permit delamination, the toughness of structures with appropriately oriented interfaces can be increased.

The problem of a crack terminating at right angles on an interface between two dissimilar but isotropic media was solved by Swenson and Rau[2] and others.[3,4] Here, we present the results for the problem of a crack impinging on an interface between orthotropic and anisotropic media with the principal material axes parallel and perpendicular to the interface. From here we develop the crack deflection criterion applicable to specific cases such as a coated Pitch-55 carbon fiber.[5] The results are condensed into a design chart that allow determining a maximum permissible interface strength for a given set of elastic constants for the coating and reinforcement if the strength of the reinforcement is also given. This treatment tells us that low modulus coatings allow us to design higher interface strengths into the composites. A higher interface strength can be translated into higher transverse strengths.

This micromechanics analysis coupled with synthesis techniques and direct measurements of interface strengths or intrinsic work of fracture values allow us to design, synthesize, and evaluate interfaces.[6,7] In short, with these tools we can engineer the material from the inside out.

In composite systems, it is often easier to measure the work of fracture. Gupta's article, "An Evaluation of the Interface Tensile Strength-Toughness Relationship," treats the relationship between the cohesive strength of the interface and the intrinsic toughness of the interface through the use of the universal bonding correlations.[8,9] This work points to the importance of segregants on the grain boundary or bi-material interfaces and of how they may control the intrinsic work of fracture and hence the cohesive strength of the interface, (which can be measured directly for model laminate systems by the laser spallation technique described in the lead article).

The thermodynamic properties of the liquid metal/ceramic interface is of interest to the materials processor and is the subject of the article by K.C. Russell, S-Y. Oh, and A. Figueredo. Silicon carbide particles are stirred into Al-Si alloys in the primary metal matrix composite commercially produced by Duralcan. Since these particles are not readily wetted by the matrix, work must be done on the system to force wetting. This work is termed the work of immersion and is equal to the difference between the wetted and the unwetted surface energies per unit surface area [$W_i = S(\gamma_{sl} - \gamma_{sv})$].

The work of immersion of a reinforcement preform can be determined dynamically from pressure infiltration experiments[10] in which the threshold pressure for infiltration is observed, or by sessile drop experiments in which contact angles are measured. A knowledge of the energetics of surfaces profoundly affects the processing economics of this class of materials.

The work of adhesion can also be deduced from these measurements and related to the intrinsic work of fracture of interfaces. Russell et al. review both the experimental and theoretical aspects of wetting of ceramics by metals, and find that recent studies of pressure infiltration of packed ceramic particulates by molten metals give fairly reliable results. Experimental measurements of surface energy and work of adhesion are both difficult and prone to experimental error, making mathematical modeling attractive.

The article goes on to review some theoretical analyses of the thermodynamics of ceramic:vapor and ceramic:metal interfaces. Quantum mechanical models, though attractive in their directness, are found to be relatively inaccurate. The most accurate model was found to be that of Eustathopoulos and coworkers,[11-12] based on bulk chemical thermodynamics. Russell et al. note that the model may not take adequate account of electrostatic effects due to charged defects in the ceramic surface region.

Whereas continuously reinforced composites are optimized at interfacial strengths between narrowly defined limits, discontinuously reinforced composites of low aspect ratio are optimized at high interfacial strength levels. For some matrices, it is the tensile strength of internal matrix planes that determines the strength and toughness of the composite; for others it is the interfacial shear strength. In "Geometrical Origins of Interfacial Strength," M.E. Eberhart, D.P. Cloughery, and J.N. Louwen point out that a material's strength is a tensor quantity having values for each applied strain but the thermodynamically based models discussed by Russell et al. use scalar quantities to predict an interfacial strength.

While such predictions have proved useful, the ultimate goal of designing interfaces with a specific combination of strengths (say particular shear and tensile interfacial strengths) will require a more complete understanding of the origins of strength. They argue that the strength of a chemical bond is not an intrinsic property of that bond but rather is related to the redistribution of electron density associated with a particular strain. For a tensile strain, a bond parallel to the direction of strain can be weakened simply by the presence of another bond perpendicular to it. The extent to which these bonds weaken each other is related to the distance between them; the closer they are the greater the effect.

Eberhart et al. apply their concepts to the $L1_0$ structures of TiAl (which is brittle) and CuAu (which is ductile). They show that the differences in mechanical properties between these two alloys can be attributed to the existence of a single bond between second-neighbor Al atoms in TiAl, whereas no such second-neighbor bond exists in CuAu. These studies indicate the potential for using quantum mechanical techniques to design interfaces as computational and experimental techniques are improved for determining the nature of the bonding at an arbitrary interface.

In the final article, H.E. Fischer, D.J. Larkin, and L.V. Interrante consider the synthesis of interfaces (or interphases) by metal-organic chemical vapor deposition (MOCVD) and polymer precursors. The authors review methods for coating fibers and ceramic bodies with metals, oxides, nitrides, carbides, and borides. Since the relative volume of material constituting an interphase is relatively small, even exotic and expensive precursors could find economic use and might be more cost effective than the vapor, plasma, or ion deposition techniques.

The field of interfaces in inorganic matrix composites is advancing rapidly. Micromechanics approaches for predicting permissible interface properties, along with the application of thermodynamic and quantum mechanical approaches to determining the bond strength of interface energies, measurement techniques, and new and novel approaches to synthesizing very specific interfaces are quickly becoming available. The dream of engineering a material from the inside out will soon become a reality.

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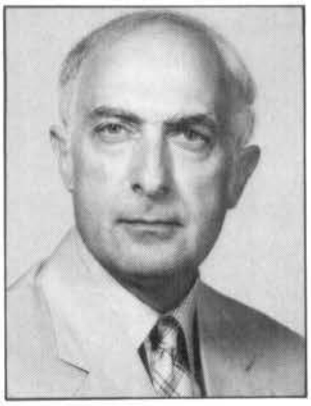
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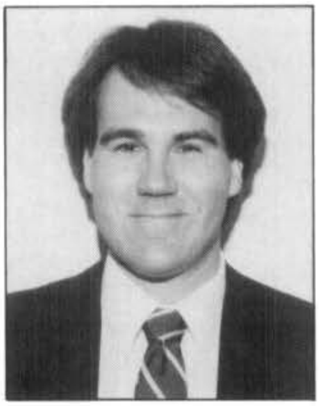
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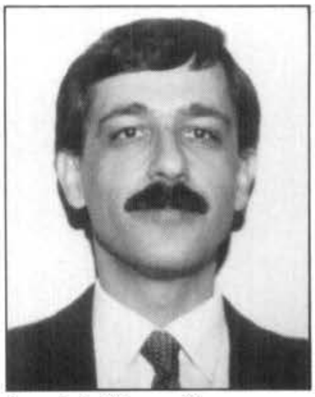
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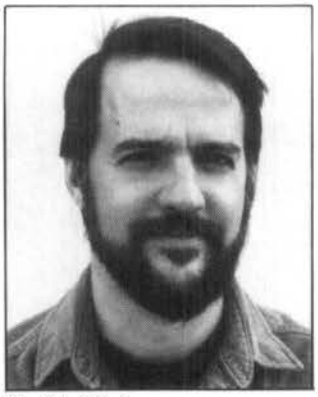
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James Cornie, Guest Editor for this issue of the *MRS Bulletin,* is director of the Laboratory for the Processing and Evaluation of Inorganic Matrix Composites of the Materials Processing Center at the Massachusetts Institute of Technology. Cornie has worked in designing interfaces for reinforcements for high temperature intermetallic matrix composites, and developing pressure infiltration casting processes for evaluating these interfaces and the mechanical behavior of reinforced intermetallic systems of technological interest. For the last 15 years, his research has involved the mechanical and chemical behavior of interfaces in metal and ceramic matrix composites, which has extended to the solidification processing of metal matrix composites, including issues of wettability and capillary resistance to infiltration and chemical degradation during processing. He received undergraduate degrees in geology and metallurgical engineering from the University of Idaho and a PhD from the University of Pittsburgh. Cornie served government and industry before joining MIT in 1983, and is a member of the Materials Research Society.

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Eric Fischer, postdoctoral associate in the laboratories of L.V. Interrante at Rensselaer Polytechnic Institute, received his PhD in organometallic chemistry from Princeton University in 1990 under the auspices of Jeffery Schwartz. Fischer is currently investigating the use of organometallic precursors in the application of ceramic coatings to carbon fibers for use in composites. His research interests also include the construction or alteration of reactive surfaces through selective attachment of organometallic complexes.

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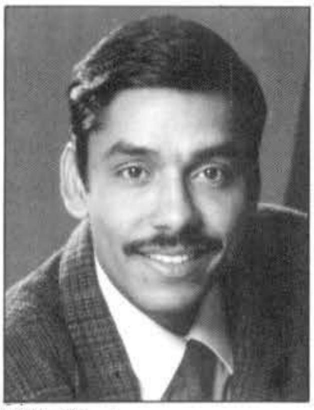
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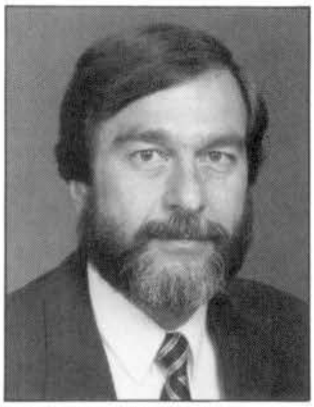
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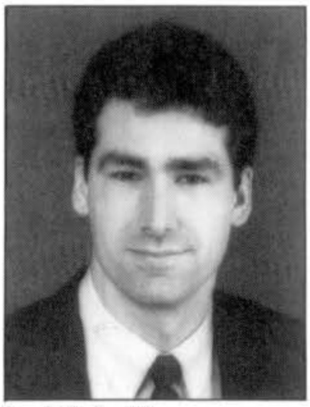
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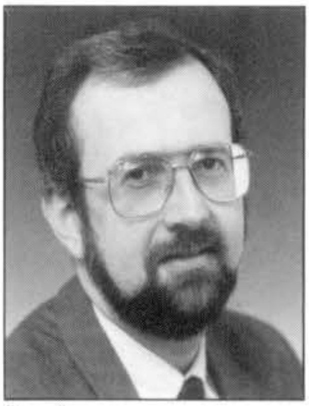
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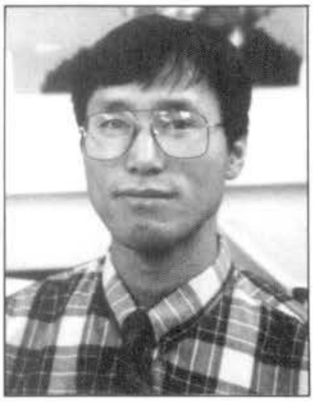
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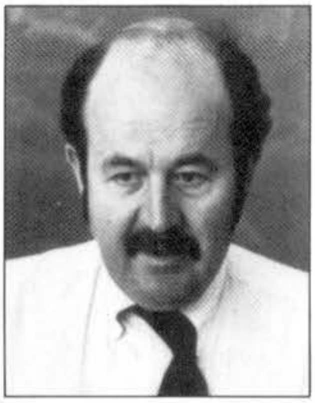
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