ods of measuring and avoiding these strains were described by a number of authors, emphasizing the enormous amount of recent research activity in the USA in the field of ceramic composites.

The Long Road of Materials Research

A most illuminating example of the subtle and complex chemical and physical problems involved in research on existing and emerging advanced materials was presented by *M. P. Harmer* (Lehigh University, Bethlehem, PA) when he gave the keynote lecture on the perennial topic "Alumina". He commented: "Twenty-seven years have elapsed since *R. L. Coble* reported that small additions of magnesia promote the sintering of alumina to full density—the LUCALOX invention. A steady succession of papers have subsequently appeared concerning the role of the additive, and a considerable amount of controversy has surrounded this topic until today. After critically reviewing what progress has been made over that twenty-seven year period in understanding the role of MgO in the sintering of alumina, I have to conclude that, although we have come a long way in understanding the phenomenology of this classic additive effect, much still remains to be done to understand the detailed mechanisms involved at the atomic level".

Many of the talks at the 90th Annual Meeting of the American Ceramic Society suggested that *Harmer*'s statement is equally applicable to most of the other major topics of current research on the processing of advanced ceramics.

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Advanced Concepts for Ceramic Toughening

A workshop on Advanced Concepts for Ceramic Toughening was held on 14–17 April 1988 at Schloss Weitenburg, FRG. The objective of the workshop was to clarify current understanding of toughening mechanisms in ceramics and to identify future patterns of work needed for the development of materials with the mechanical properties required for applications.

The meeting was divided into four sections concerned respectively with the theory of toughening mechanisms, with the role of interfaces in toughened microstructures, with the requirements of processing and with the transfer of these concepts into industrial practice. An additional discussion session was devoted to the significance of toughness for the acceptability of ceramics.

It was recognized that different sectors of the subject were at very different levels of development. Thus, work on transformation toughening had been brought to a level of maturity where significant issues remained but where the basic understanding was now sound. In contrast, work on fiber and whisker reinforcement was at a very preliminary level in terms of the understanding of the desired interface structure between the reinforcing phase and the matrix. There was in particular concern that high temperature events in toughened microstructures had received little attention and were not well understood.

Toughness and Microstructure

The majority of contributions in this session were concerned with transformation toughening and this subject was also emphasized in the discussion. The common opinion expressed in the summary was that the understanding of transformation toughening is already very high; we have a good understanding of the microstructural contributions (grain size, grain shape, glassy phase, inclusions, etc.) to the toughness. In general it is possible to tailor a microstructure towards a desired toughness.

In selecting particular items from the session, ceria-stabilized tetragonal zirconia (Ce-TZP) is seen as a new material in the group of transformation toughened zirconias. The strongly nonlinear crack diffraction curve will be a subject for many investigations in the future. The origin for the curve is the unusual transformation zone which reaches far ahead of the crack tip and whose shape and elongation are not yet understood. The crystallographic origin of this shape is probably the related transformation tensor, which is not known and which has to be investigated. The scatter of the mechanical properties, especially that of the K_{Ic} values, is dramatic and reaches from just 5 MPa m^{-1} to over 30 MPa m^{-1}. There is strong evidence for a microcrack mechanism in this material; however, the microscopic proof for this is still missing. For this material, the fracture mechanical description using only a K_{Ic} value is no longer valid and has to be replaced by a set of *R*-curves.

Interfaces

Compared to transformation toughening, the understanding of the role of interfaces is pretty weak. The audience agreed that experiments on the characterization of interfaces in model systems and, of course, in practical systems are missing. For most materials the fracture energies

for the interfaces are not known; thus the effect of inclusions on crack propagation cannot be predicted theoretically. In particular the characterization of interfaces at the high temperatures encountered in many applications has not been investigated and is surely a subject for the future.

Basically, a similar judgement can be made for reinforcement with ductile particles. It is already known that a certain degree of debonding at the interface between the ductile particles and the brittle matrix is wanted in order to allow an extended deformation of the particle. However, numbers such as the required percentage of debonded surface, the optimal inclusion size, the preferred level of ductility, etc. are not known and have to be measured in the future. For the technical application of ductile particle reinforcement, long term properties such as corrosion, wear, oxidation behavior, etc. have to be taken into account.

Acceptability of Ceramics

The measurements on fatigue, i.e. the degradation of strength under cyclic load, were the most exciting and impressive news in the discussion session. The fact that toughening and resistance to fatigue are contradictory targets has not been recognized until now; microstructural optimization and design have been directed only to the improvement of the K_{Ic} value. For the future, of course, microstructural design has to consider long term properties. The description of materials behavior in terms of fracture mechanics is losing its dominating importance, i.e., consideration of long crack behavior will be one part of the truth which must be supplemented by the mechanics of short cracks. Hence, fatigue, subcritical crack growth, and creep will recieve more attention.

Brittle materials have been described by one K_{Ic} value and non-linear materials by just one R curve. However, R curve measurements with different starting crack length have shown that the slope of the R curve depends on the length of the initial crack. A complete description of the materials properties thus requires the knowledge of a whole set of R curves. Materials designed with contact shielding (crack surface interactions behind the crack tip) will be very difficult to describe and many measurements must be done in the future.

Processing

The discussion of the processing session was relatively short. The wet chemistry processing routes for single phase powders are standard techniques now and will be optimized in the future. Whisker and fiber reinforced systems will require hot isostatic pressing or hot pressing for densification. However, when these materials are densified at a certain temperature they will not be able to carry load in this same temperature range (creep, oxidation etc.). Consequently, non-sintering processing routes are being developed such as gas phase infiltration, liquid phase infiltration, displacement reactions and melt-oxidation. Undoubtedly these preparation techniques will attract more attention in the future.

Applications

This session was planned to link the basic scientific aspects with industrial applications. It is obvious that there is a need in industry for more damage tolerant materials, and industry therefore welcomes the newly developed ceramics. But it has to be stated that toughness and high K_{Ic} values are not the only properties required of a material. The relationship between different properties, and the response of the behavior of a material to various microstructural modifications have to be studied. A conflicting relationship between toughness and fatigue is already visible. This is not an unusual situation in the development of materials: in metallic systems, an understanding of the properties-microstructure relationship has been a prerequisite in applying these materials safely in well designed constructions. In the future one has to study the effects of preparation conditions on the microstructures and the correlation between microstructures and properties, with toughness being one important parameter. These studies will be done in the area of basic science with feedback, however, from the applications side.

The meeting was encouraging in that it demonstrated the progress that could be made with a topic such as transformation toughening when the resources of the materials community were focussed on its solution. The meeting raised matters of real concern in respect to the possible fatigue penalty which could ensue from the use of toughening mechanisms, and in particular with respect to the absence of identified toughening mechanisms suitable for high temperature applications. The two topics were seen as a suitable basis for future research programs which could then be reported at a subsequent workshop.

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