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ADVANCED ENGINEERING MATERIALS AT HIGH TEMPERATURES

L. CARTZ - *Consultant*

Marquette University, Milwaukee, Wisconsin, USA

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Abstract

Materials that are available at the present time for use as engineering components are highly limited in their performance at temperatures above about 1000°C in corrosive environments. There is probably no satisfactory material for service in air above 1400°C and there is only a restricted selection of materials in view including silicon nitride based materials, silicon carbide based materials, and carbon-carbon-silicon carbide composites.

This article summarizes the findings of several recent workshops concerned with high-temperature engineering ceramics, and covers nitrogen ceramics, ceramic-ceramic composites, ceramic coatings, ZrO₂-based ceramics, non-oxide ceramics, ceramic toughening mechanisms, and the microstructure and processing of engineering ceramics.

Progress towards improved ceramic properties is not automatic, and many severe problems remain. Developments are needed in Oxidation resistant coatings for carbon-carbon composites, and for super-alloys;

Particulate dispersants of controlled morphology suitable for Si₃N₄-based and SiC-based materials;

High-stability fibres with non-reactive interfaces in refractory matrices;

Sintering mechanisms of monolithic and of composite ceramics;

Other high-temperature materials such as borides, silicides, carbides;

Detection of small flaws in ceramics;

Data on the mechanical properties of ceramics at temperatures above 1400°C;

Other methods of preparation of ceramic microstructures;

Ceramic toughening mechanisms and their interactions.

1. Introduction

There is considerable interest in the development of engineering materials for use at temperatures well above 1000°C, and at temperatures as high as possible. These materials are required for service as components of engineering systems such as gas turbines, reciprocating engines, or energy conversion applications (29,32,34,25). Several workshops and conferences have been held over the past few years to discuss both the progress and the problems facing the preparation and utilization of these advanced materials, particularly ceramics which must be employed once the working temperature exceeds about 1200°C (1-8,10,17,19,42,43).

A workshop "Engineering Materials for Very High Temperatures", which will be referred to as WI, was held in 1987 at the University of Warwick, England, organized by the Office of U.S. Naval Research, (ONRL) in conjunction with the Institute of Physics, U.K. (1,2). Another workshop, which will be referred to as WII, was held on "Advanced Concepts for Ceramic Toughening" in April 1988 at Stuttgart, W. Germany (3). Several other meetings have also been held on the topic of ceramics for high temperature engineering purposes and some of these are listed in references 4-18,94.

This review is based in particular on the two workshops WI and WII mentioned above (1-3). The organizing committee of workshop WI included P. Popper (92), D.P. Thompson (67,64), M.H. Lewis (70-76), and L. Cartz (1). The workshop WII was organized by the staff of the research institute directed by G. Petzow (58). The materials and topics covered include nitrogen ceramics, ceramic-ceramic composites, ceramic coatings, ZrO₂-based ceramics, and non-oxide ceramics. The subjects discussed cover ceramic toughening mechanisms, microstructure, and the processing

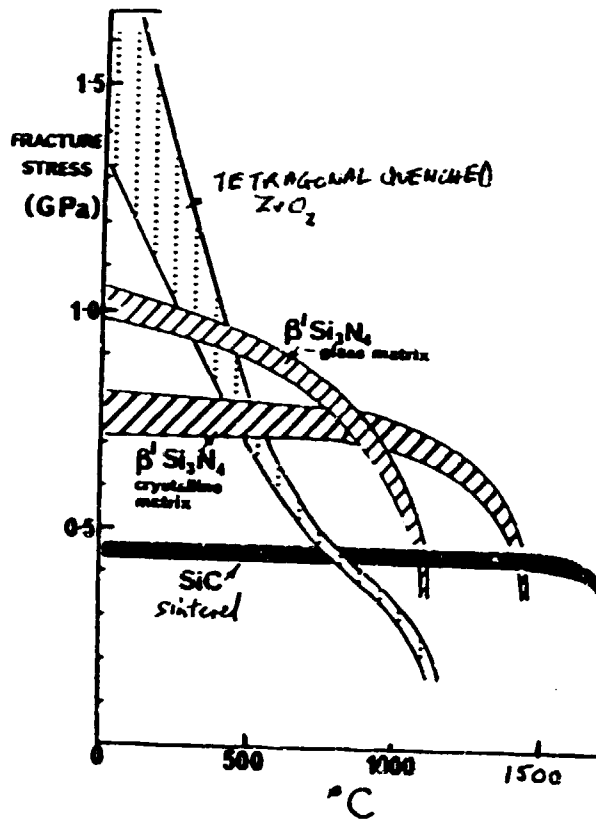
of engineering ceramics. Some general comments are given on the limitation of present day materials for high temperature uses, as well as an outline of future research initiatives.

A listing is presented of various European research programmes and societies concerned with materials developments.

2. High Temperature Engineering Ceramics

A well-balanced review and assessment of the behavior of ceramics at high temperatures has been developed by Lewis (1,70-76) in which microstructural mechanisms are described and related to the achievement of improved performance at high temperatures. These microstructural features, and methods of their preparation are illustrated in Figs. 1-3. In Fig. 1, the changes of fracture stress with temperature are presented for some of the more interesting high temperature ceramics materials. The properties of solid state sintered SiC are superior at temperatures above approximately 1,000°C though inferior to the properties of Si₃N₄- and ZrO₂-based ceramics at lower temperatures (13,27). In Fig. 2, microstructural features are illustrated which provide mechanisms of improved mechanical behavior; micro-cracking (77) of a sub-critical brittle crack, crack-deflection and bifurcation of a sub-critical brittle crack (78), crack-bridging and pull-out by anisotropic particles in the wake of a sub-critical brittle crack (1). Creep deformation at higher temperatures depends on grain-boundary shear and diffusion; creep rates become significant at high temperatures when glassy-phase residues from liquid-phase sintering are present at the grain boundaries.

The microstructure of a ceramic material depends on the fabrication method and many of these are illustrated in Fig. 3. Solid state sintering (Fig. 3A) can be used in a limited number of cases, such as SiC with additives of boron and carbon to obtain a nearly equi-dimensional grain morphology. Liquid-phase sintering is necessary for Si₃N₄-based ceramics (Fig. 3B), leaving a glassy phase; an example is the formation of anisotropic grains of BSi₃N₄ with a 10 volume percent of a silicate phase



The variation with temperature of the fracture behavior of SiC, Si_3N_4 and ZrO_2 -based ceramics. The sintered SiC has superior properties at high temperatures (70-76).

Fig. 1

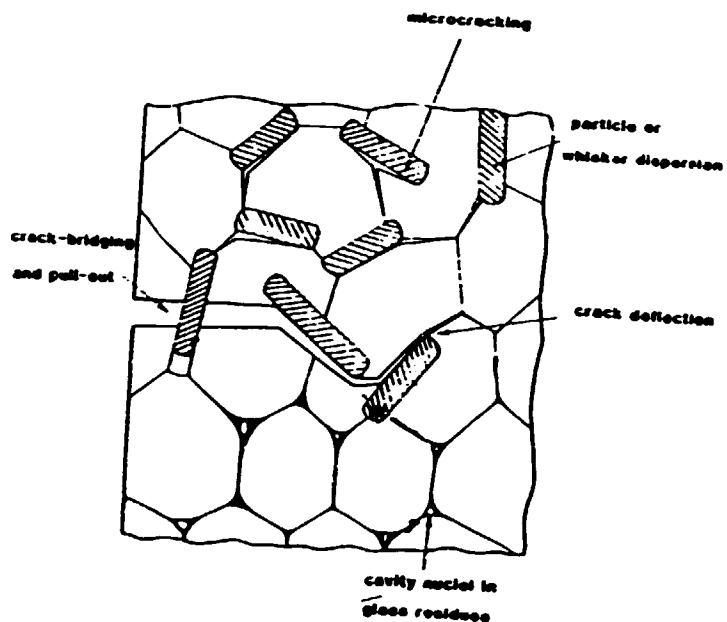
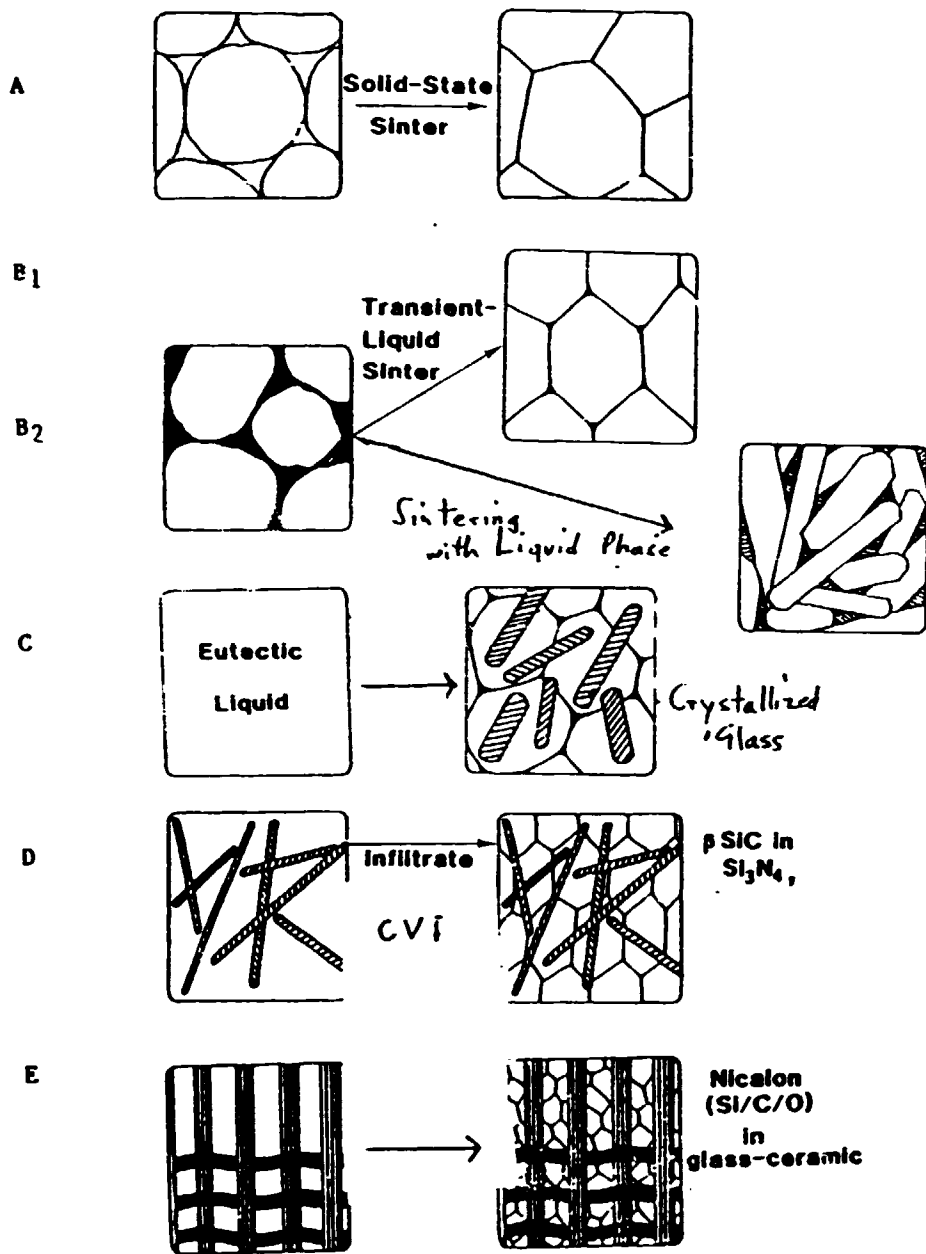


Illustration of microcracking, crack deflection, crack-bridging, pullout, particle dispersion, whisker dispersion, and glass-residues in ceramic microstructures. These represent mechanisms modifying the mechanical properties of the ceramic material (70-76).

Fig. 2



Ceramic microstructures developed by different fabrication methods (70-76).

- A Solid state sintering; e.g., SiC with B and C additives
- B₁ Liquid phase sintering (transient); e.g., hot pressed Si_3N_4 with Mg and Al additives
- B₂ Liquid phase sintering; e.g., $\beta\text{Si}_3\text{N}_4$ and glass
- C Crystallized glass; e.g., $\text{Si}_2\text{N}_2\text{O}$ with yttrium aluminum garnet additive
- D Composite of random whiskers with infiltrated matrix; e.g., βSiC in Si_3N_4 (84)
- E Composite with oriented (woven) continuous fibres, infiltrated by matrix (21); e.g., Nicalon fibres (SiC+O) in glass-ceramic matrix (82) or with vapour infiltration of SiC (83)

Fig. 3

having a eutectic temperature approaching 1600°C. This has enhanced fracture toughness but also limited high temperature applications (93). The glassy phase can become fully crystalline as in the case of yttrium aluminum garnet (YAG) (74), or the glass phase can be transient (73) with the formation of a solid solution in the matrix phase. Another method of preparation is by the crystallization of a refractory oxynitride glass to form an oxide-oxynitride ceramic (Fig. 3C).

Other methods of preparation involve composite structures where random arrangements of short fibers, or woven arrangements of continuous fibers are impregnated with a matrix material by chemical vapor infiltration (CVI) (16,28), or by a glass-ceramic process (81); see Fig. 3D and E.

The microstructure of a useful ceramic should probably be multiphase, with crystals highly anisotropic in shape, whisker- or needle-like, with no glassy phases present. Liquid phase sintering is a useful method of fabrication, so that methods of crystallizing the glass residues are advantageous. An example of this is the use of a crystallizable M-Si-O-N glass, with hot isostatic pressing to keep the required quantity of glass to a minimum (1).

The presence of intergranular glass can result in increased values of the critical stress-intensity factor K_{IC} at high temperature due to viscous deformation of the glassy form. However, glass residues lead to time dependent failure, due to creep-cavitation in glass residues (71), limiting use to below 1000°C. Whisker, fibre and particle dispersions can also improve K_{IC} , but these particle dispersions tend to degrade at high temperature when the interface fibre-matrix tend to react (85,33). There are high temperature effects on the SiO₂ protective coating which

degrades by reactions when oxides are present, such as YAG (75), or by reactions with NaCl (86).

3. Nitrogen Ceramics and Silicon Carbide

Existing silicon nitride and sialon-based ceramics can currently be used up to 1300°C and it can be expected to increase the temperature to 1400°C by improvement in heat-treatment procedures with minimum levels of additives (37,20,65).

The serious problems requiring solution have been discussed in several recent meetings (5,6,37,41,27) and these concern in particular

- oxidation problems of nitrogen ceramics
- the glassy phase in silicon nitride and sialon ceramics
- chemical compatibility; for example of SiC and sialon (66)

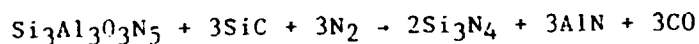
Catastrophic oxidation cracking of nitrogen ceramics occurs at about 1000°C when yttria, magnesia, or niobia are added as densifiers (35).

The microcracking of the ceramic can be related to the volume change on oxidation of the phases of Y, Mg or Nb located usually in the glassy phase at the grain boundaries. Methods of reducing the volume changes decrease the extent of the microcracking, as does the presence of some residual glassy phase at the grain boundary which can tolerate some strain elastically (20,36,38,64).

The mechanical properties of high temperature silicon nitride ceramics deteriorate due to the glassy phase at the grain boundaries. This necessitates using the minimum of sintering additives, changing the wettability of the glassy phase at the grain boundary, and avoiding impurity segregation at the grain boundary. Further improvement to mechanical properties is by forming composite-type structures. The glassy phase at the grain boundary can be reduced by using a glass of lower wettability and lower oxygen content when the glass tends to locate at triple points.

Compositional changes can be made so that no glass phases form, for example by the use of Si-Be-O-N compounds, or by causing the glass to crystallize to a refractory compound, as occurs in the presence of Y_2O_5 . Improved properties of silicon nitride ceramics at high temperatures depend on the use of the minimum amounts of sintering additives, using pure powders, and by the formation of composite microstructures to cause grain boundary pinning.

Hendry (66) discussed the chemical compatibility of SiC-sialon composites. SiC and Si_3N_4 are both relatively stable and do not react together at high temperatures so that it had been assumed that SiC with sialon do not react together; this is not so and a reaction does occur, such as



Other topics reviewed at conferences (5) and (6) include

Transparency of nitrogen ceramics (67)

Precursors of SiC and Si_3N_4 (68)

The Ti-N system (5)

The reaction of AlN and ZrO_2 (69)

4. Ceramic-Ceramic Composite Materials

A range of research studies and technological developments on ceramic-ceramic composite materials have been carried out over the past few decades. The main ceramic-ceramic composite systems under development have been:

- C-C composites with woven continuous fibre
- SiC-SiC
- Si nitride with ceramic whiskers
- SiC with ceramic whiskers
- SiC unidirectional fibers in a SiO₂ matrix
- SiC fiber in a refractory silicate glass ceramic.

A discussion of the ceramic-ceramic composites developments in France has been presented by Jamet (16) as part of the workshop WI, and several of the comments are given here. Recent work in West Germany is discussed in reference (92).

Ceramic fibre reinforced ceramic composites have been considered for high temperature applications between 1200 and 2500K which require low weight, high strength, high toughness, high temperature resistance, and damage resistance. High performance fibres, such as C, SiC, Al₂O₃ (24, 30,31) are available and densification of fibrous composites can be carried out by chemical vapour or liquid infiltration. The importance of multidirectional weaving of the fibres in composites has been demonstrated (33). At temperatures up to 2500 K, survival of the composite requires chemical compatibility of the components with the ability to withstand oxidation (42). Carbon-carbon composites have excellent mechanical characteristics up to 2500 K in reducing atmospheres but require a protective coating in air (22,25,32,42). Composites using refractory

components such as oxides, carbides, or nitrides are limited at high temperatures by

- the intrinsic stability of the components to grain growth and creep;
- diffusion or reactions between components requiring the control of the interface;
- fiber sensitivity to external agents particularly oxidation resistance;
- diffusion of these external substances through the matrix;
- reactions between the matrix and external substances.

Several methods exist to protect carbon-carbon composites against oxidation, and the most common method is based on Si-compound coatings chemically compatible with carbon, resulting in the formation of a protective coating of SiO_2 (26,42). This can be achieved using SiC, though there are many limitations including

- chemical, thermal, and mechanical bonding between the carbon composite surface and the SiC coating
- hermetic sealing of the composite
- protection against rapid oxidation leading to catastrophic

failure.

The protective coatings can be formed by chemical vapour deposition of SiC at low pressure which gives a good infiltration of the carbon-carbon composite suitable for applications at high temperature, low pressure and low mechanical stress. Another method uses silica or silica glasses prepared by the sol-gel method. Reviews of coatings and surface treatments for high temperature oxidation resistance have been published recently by Saunders and Nichols (22) and Harris and Lutz (25). Ceramic

composites using carbide, nitride, silicate, oxycarbonitride matrices with fibres are reviewed in references (59-61). The only composite compositions capable of extended use above 1000°C are found to be SiC-SiC and C-SiC (61).

Jamet (16) has concluded that carbon and silicon compounds, especially silicon carbide with its silica protective layer, seem to be the two main materials able to maintain very high temperature stability and thermostructural properties above 1000°C in spite of their oxidation sensitivity. With additional protection, SiC-SiC chemical vapour infiltration and C-SiC chemical vapour infiltration can be used safely at 1300° and 1600°C respectively. They can also sustain higher temperatures for a brief time. Carbon-carbon composites can be used at 1600°C with an efficient silicon compound protection and this ceramic-ceramic composite is very promising.

SiC Nicalon continuous fibers and SiC whiskers are the principal ceramic reinforcements used at present with various ceramic matrices. The long fiber may be used up to 1350°C if its oxidation protection remains intact. The SiC whiskers are very promising for higher temperatures.

Below 1000°C, several ceramic composites are in use and reinforced glass-ceramic composites show the best performance in this temperature range (62).

At the meeting on ceramic-ceramic composites in Mons, Belgium (1987), see reference (4), the topics discussed included

- homogeneous dispersion in multicomponent systems
- SiC-fibre reinforced composites (62)
- Zr-C-O system (63)

The homogeneity of ceramics of complex compositions depends on obtaining homogeneous dispersions. Sintering rates depend on density, composition, and are adversely affected by the presence of non-sintering inclusions such as fibres. Sintering can be improved by inducing comparable shrinkage of the fibres by the application of an organic coating which is driven off at temperature. Other methods are reaction sintering (69), reduced viscosity by employing smaller grain sizes, liquid phase sintering, and by the use of hot isotatic pressing.

SiC-based composites have been investigated by Dawson et al (62), and Zr-C-O ceramics by Barnier and Thevenot (63).

5. Ceramic Toughening Mechanisms

The methods available to improve the properties of ceramic materials have been reviewed at the workshop (WII) on "Advanced Concepts for Ceramic Toughening" held in Stuttgart, W. Germany in (1988). An extensive summary is provided here of the workshop; (3), see also (2), p. 5.

The workshop WII considered toughening mechanisms for ceramics of improved performance, and set out to determine patterns of work required for future improvements. The sessions at the workshop were concerned with

- toughening mechanisms; chairman A.G. Evans (87)
- the role of interfaces; chairman A.H. Hever (88)
- the requirements of ceramic processing; chairman R.J. Brook (89)
- toughness and ceramic applications; chairman D. Marshall (90)

The toughness mechanisms considered included

- transformation toughening
- toughening by ductile phase
- toughening by brittle fibres or whiskers
- toughening by microcracks and crack bridging

Transformation toughening discussions covered topics including ferro-elastic transformation, for which little evidence exists at present, twinning transformations, the transformation zone, and the synergism of toughening mechanisms. It is also necessary to determine resistance curves of toughness as a function of crack elongation, R-curves, using standardized specimen geometries.

Toughening by ductile reinforcements require high flow stresses and plastic stretch, possibly involving dislocation pile-up, and the trapping of cracks by ductile particles.

Toughening by brittle fibres and whiskers depend very much on the interface between fibre and matrix. Fibres must be able to debond to some extent from the matrix as a crack propagates. The elastic moduli of fibres and matrix need to be similar, and the debonded layers of matrix and fibres should have low friction coefficients. Special coatings and surface treatments of fibres are important, and the thermal expansion of fibre and matrix should be closely related though some residual stresses are important for good mechanical properties. Aligned fibres are much more effective than random orientations of fibres.

Microcracking and crack-bridging toughen some polycrystalline oxide materials, though there is uncertainty and controversy about the toughening mechanism. Frictional locking, grain boundary locking, and anisotropic grain sizes are considered to play a role. Microcracking is known to toughen alumina-zirconia ceramics.

The role of interfaces (88) is important in glass, alumina and Si_3N_4 matrices, reinforced by SiC fibres or whiskers. The whiskers used are frequently Tatecho or Arco of variable diameter, with an amorphous SiO_2 rich surface layer and a low density inner core. SiC whiskers in alumina matrices are under compression, whilst SiC whiskers in Si_3N_4 matrices are under tension. Debonding, crack deflection, crack binding, the damage of propagating cracks, and chemical reactions at the interface at temperatures above 1000°C all require detailed consideration.

Optimization of the method of applying reinforcement fibres or whiskers are required as well as understanding the diffusion and chemical reactions at the interface. Better methods of testing are required at high temperatures (17).

The nature of the parameter 'toughness' used for ceramics needs to be clarified (90). Fatigue in toughened systems, hysteresis in loading/unloading, and fatigue and propagation rates with stress intensity, all of these depend on the toughness mechanism. In continuous fibre composites, multiple cracking mechanisms take place so that failure does not occur by the growth of a single crack. No single parameter of toughness can describe all these properties of ceramics.

Ceramic processing (89,90,40) is required for ceramics with equidimensional grain structures, as well as for whisker-fibre reinforced structures. Whiskers and fibres present difficulties in achieving high densification due to back stresses arising from the non-sintering components as well as shrinkage anisotropy.

Very fine powder sizes give rise to a dense yttrium doped tetragonal ZrO_2 of equi-axed grain sizes of about $0.1 \mu m$. Superplasticity ZrO_2 -mullite can be used to prepare dense components. Reaction sintering (ZrN with TiO_2 to form ZrO_2 with TiN) has been used to form dense ceramics (69).

It is necessary to obtain good homogeneous suspension of powder-whiskers (or fibre) with additives in order to sinter to a homogeneous ceramic. Control of pH and low fibre loading below 15 volume % are generally needed to overcome anisotropic shrinkage and to achieve high densities.

6. Present-day Materials and Future Research

General reviews have been presented at several recent workshops and conferences (1-3) on the limitations of present day engineering materials for use at high temperatures, under high stress, and in corrosive environments. Meetham (44) has discussed the future requirements of gas turbine components such as aerofoils, discs and combustors where nickel super-alloys permit the use of gas turbines up to about 700°C. Metseelaar and Wolff (45) have described the requirements of a thermionic energy converter operating at 1450°C for which a trilayer material has been designed consisting of a tungsten emitter coated with a diffusion barrier of TiN and an outer protective shell of SiC. Nickel (29) has discussed the requirements of core materials for advanced high temperature reactors. Van der Sluis (39) has reviewed the brazing of oxide and non-oxide ceramics to metals.

At the workshop (WI) on "Engineering Materials for Very High Temperatures", all possible materials and treatments were considered including N-ceramics, ceramic-ceramic composites, carbides, borides, silicides, and refractory silicates. The properties demanded are high strength, toughness, creep resistance, and oxidation resistance at high temperature, but cost-effective processing and reliability are equally important.

The following summary discussions are taken from workshop (WI). Among the ceramic materials silicon nitride-based ceramics allow use up to about 1250°C, which might be extended to 1400°C. Current ceramics based on Si₃N₄ and on sialons have probably the best balance of strength-toughness at temperatures up to 1300°C. Monolithic silicon carbide has a better performance at high temperatures but suffers from a low fracture toughness. Carbon-containing materials could be used at temperatures of

perhaps 2000°C, but for the use of these materials in air, protection against oxidation needs to be provided, which is not an easy problem to solve. The same applies to the protective coatings on refractory metals, which require a better understanding of coating adhesion and diffusion properties.

The fracture toughness of ceramic materials might be increased by the incorporation of fibers and whiskers. This approach is limited by the availability of suitable fibers and whiskers. Current composite materials do not display better fracture toughness properties at high temperatures than monolithic ceramics. The mechanism of sintering without the formation of liquids, as in the sintering of silicon carbide, requires elucidation.

There is a modest understanding of microstructure and property relationships in high-temperature creep, fracture, and oxidation of monolithic ceramics. Monophase ceramics, exemplified by solid-state-sintered SiC, have good time-dependent properties up to 1600°C (93) but have microstructures with a poor fracture toughness, of the order of 5MPa/m. Some improvement in fracture toughness (6-8 MPa/m) is attainable in liquid-phase-sintered Si₃N₄ and sialon ceramics, which retain good creep, creep-rupture, and oxidation resistance at 1300°C provided that the liquid residues are fully crystallized. Instability in oxidizing conditions above 1350°C may be improved by reducing the residual glass phase content and using hot isostatic pressing (HIP) fabrication, but fracture toughness is generally reduced.

Composites have a potential for removing one of the most important engineering design limits of monolithics, that of microscopic critical

flaw sizes associated with low fracture toughness. Useful increments in toughness (10-15 MPa/m) are attainable by the dispersion of whiskers (10-30 volume percent) in various matrices, retaining conventional fabrication procedures but normally requiring pressurized sintering. Although they exhibit impressive unidirectional fracture properties, there are significant problems in high-temperature stability of non-stoichiometric fibers (such as Nicalon-SiC), in the fabrication of refractory matrices with nonreactive fiber-matrix interfaces, and in the forming of three-dimensional woven-fiber component shapes capable of retaining a large fraction of the unidirectional property. High-temperature deformation and creep-fracture of both fibrous and whisker composites remain a relatively unexplored field.

The more complex, difficult, and hence expensive fabrication processes for high-temperature monolithic ceramics, and especially for composites, must be weighed against the increase in high-temperature performance over the lower temperature superalloys. The "Lanxide" process, in which a liquid metal matrix is converted to an oxide ceramic, is of particular interest in the formation of monolithic and composite ceramic shapes. Incomplete metallic conversion is beneficial for fracture toughness, but it clearly presents problems in relation to high-temperature operation above the liquidus of the metallic residue.

The recommendations made at workshop WI are as follows:

Near-term Studies

- Increasing the temperature ceiling of Si_3N_4 -based monolithic ceramics to at least 1400°C in oxidizing conditions, using stable crystalline sintering residues and HIP processing.
- Improving the fracture toughness and strength of SiC-based cera-

mics, formed by solid-state sintering, by particulate or whisker dispersions, while retaining the good creep-rupture and oxidation resistance of the sintered matrix.

- Further development of SiC or carbon-based fibrous composites with respect to stability at temperatures of 1200°C, especially in oxidizing conditions, for example by coatings for carbon-carbon composites and the use of the newly emerging stoichiometric SiC fibers.
- Development of coatings on metals, such as superalloys, replacing existing oxide coatings by refractory silicates (celsian, for example) of matched thermal expansion behavior.

Long-Term Studies

- The development of a range of new particulate dispersants, with controlled morphological anisotropy, and chemical compatibility with Si₃N₄ and SiC-based matrices, designed to extend the principle of "whisker-toughening."
- Further development of high-stability fibers, such as stoichiometric SiC, and of nonreactive interfaces with refractory matrices. This may be achieved by coatings or by using lower temperature fabrication such as the "sol-gel" route for oxides, or "reaction-bonding" for Si₃N₄. The present-day limited choice of fibers is a severe handicap; it would be very useful to have fibers of materials such as BN, BC, and AlN.
- Development of shaping-fabrication procedures, especially for fibrous composites, with an emphasis on specific component applications.
- Develop a better understanding of the basic mechanisms involved in sintering, both of monolithics and composite matrices, and of high-

temperature deformation and fracture. In "dispersed-phase" composites, the relative contributions of different toughening mechanisms should be investigated.

- Develop an understanding of coating cohesion and substrate interdiffusion.
- Examine the properties of other high-temperature materials, such as those based on borides, silicides, and carbides.
- Develop methods of flaw detection in ceramics to permit the study of the smallest flaws under stress and environment, as well as to obtain more consistent properties in ceramic materials.
- There is a lack of data of the mechanical properties of ceramics above 1400°C, and data is required certainly up to 1600°C. Measurement techniques to acquire this data need to be developed (9).

At the meeting on engineering ceramics at Coventry, UK, July 1987 (7) the following specific points were made concerning problems arising when metals are replaced by ceramic materials:

- Sharp corners must not be present in the ceramic component so that redesigning of a component is essential.
- Ceramics absorb gases and liquids, and precautions must be taken.
- Catastrophic failures in ceramics do occur so that a very large safety margin must be used in the design.
- There is no standardization in the testing of ceramics.
- It is best if the ceramic component can be held under compressive forces.
- It can be very difficult and expensive to obtain precise shapes or ceramic components; the use of diamond grinding is very expensive and should be avoided if at all possible.

At the workshop WII on "Advanced Concepts for Ceramic Toughening" (3), the following research initiatives were listed.

The nature of fatigue mechanisms in ceramics and the prevalence of fatigue for different ceramic systems are not well understood and are of major significance for applications. The relative importance of fatigue in toughened ceramic microstructures must be assessed to guide microstructural design for such materials.

The use of ceramics at high temperature suffers from the relative lack of characterization of microstructures and failure mechanisms at high temperature. The refinement of high-temperature testing and the specific design of microstructures for high-temperature stability and toughness are important research tasks.

Research requirements identified are as follows (3):

R-curves	Agreed geometry for testing Calculation of curves for specific mechanisms
Synergism	Nature of interaction between different toughening mechanisms
Ductile phase toughening	Plasticity of constrained particles Studies of bridging zone behavior Control of particle-matrix interface
Fibers, whiskers	Nature of fiber-matrix debonding Design of interface coatings of suitable stability and bonding
Microcracks	Modeling of toughening behavior Assessment of prevalence of the mechanism
Interface-Microstructure	Debonding phenomena for fibers and particles Characterization and testing at high temperature
Densification of composites	Evaluation of limits for pressureless densification and identification of impediments

Whiskers and fibers	Availability of reinforcement phases of controlled microstructure.
Fine grain size	Extension of processing capability to finer powder sizes
Reaction sintering	Preparation of required composite microstructures by in situ reaction

7. European Materials Research Activities

The new European Ceramic Society, ECS, has been established recently with the first European ceramic conference being held in Maastricht, the Netherlands in June 1989. So far, the countries adhering to ECS include France, Italy, Western Germany, the Netherlands, Belgium, the United Kingdom, and Spain. Further details about ECS can be obtained from the president of the society, Professor R. Metselaar, Secretariat European Ceramic Society, Centre for Technical Ceramics, Eindhoven University of Technology, Eindhoven, the Netherlands.

A new European Society of Materials has recently been established by an agreement signed December 1987 by the Deutsche Gesellschaft für Metalkunde, The Institute of Metals (UK), and la Societe Francaise de Metallurgie. It is hoped that other European societies of metals, ceramics, and other materials will join the federation.

The objectives of the federation are to:

- Improve the dissemination of information about the scientific meetings of the individual national societies
- Increase the participation in national meetings, including sponsoring European meetings
- Publish simultaneously scientific reviews of metallurgy in German, English, and French
- Hold an annual major European meeting on materials.

Further information can be obtained from these addresses:

La Societe Francaise de Metallurgie, 1-5, rue Paul Cezanne, 75008 Paris, France. [Secretary General Yves Francot, Tel: 1-45-63-17-10]).

The Institute of Metals, 1, Carlton House Terrace, London, SW1Y 5DB, UK, Secretary Sir Geoffrey Ford, Tel: 1-839-4071.

Deutsche Gesellschaft für Metalkunde, Adenauer-Allee 21, D-6370
Oberursel 1, West Germany.

A Federation of Materials Institutes has been formed in London, UK, by the amalgamation of the Institute of Metals, the Institute of Ceramics, and the Plastics and Rubber Institute. The new Federation will be able to cover the entire field of Materials, and it is contemplated that eventually a single Institute of Materials will be formed in the U.K. The Federation will be governed by a council consisting of the Presidents of the founding societies. Further details may be obtained from Sir Geoffrey Ford, the Institute of Metals, 1, Carlton House Terrace, London SW1Y 5DB, UK.

European Programs in Materials Science and Technology

There is a wide range of European programs of collaboration in the fields of science and technology set up by the Commission of the European Communities (CEC) and a selection of these programmes are listed in Table I (47,48).

Table I. Some Acronyms of the European Scientific and Technological Research Programs and Organizations

BRITE	Basic Research in Industrial Technologies for Europe
CCFP	Consultative Committee for the Fusion Program
CEAM	Concerted European Action on Magnets
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CERN	European Organization for Nuclear Research
CERT	European Parliament Committee on Energy, Research and Technology
CIT	Committee on Innovation and Technology Transfer
CODEST	Committee for the European Development of Science and Technology
COMETT	Community Action Program for Education and Training for Technology
COST	European Cooperation in the Field of Scientific and Technical Research
CREST	Scientific and Technical Research Committee
CST	Euratom Scientific and Technical Committee
DELTA	Developing European Learning through Technological Advance
DESY	German Electron Synchrotron
DIANE	Direct Information Access Network for Europe
EAEC	European Atomic Energy Community
FARN	European Academic and Research Network
ECSC	European Coal and Steel Community

EDPEC	Energy Demonstration Program of the European Communities
EIRMA	European Industrial Research Management Association
EISCAT	European Incoherent Scatter Radar Facility
EJOB	European joint optical bistability project
ERASMUS	European Community Action Scheme for Mobility of University Students
ERS	Earth Resources Satellite
ESA	European Space Agency
ESEP	European Science Exchange Program
ESF	European Science Foundation
ESO	European Southern Observatory
ESPRIT	European Strategic Program for Research and Development in Information Technology
ESRC	European Science Research Councils
ESRF	European Synchrotron Radiation Facility
ESTEC	European Space Research and Technology Center
EURAM	European Research on Advanced Materials
FUREKA	European Research Coordination Agency
EUROMET	European Collaboration on Measurement Standards
FAST	Forecasting and Assessment in Science and Technology
FEICRO	Federation of European Industrial Cooperative Research Organizations
FP	Framework Program
FTSC	Fusion Technology Steering Committee

IRDAC	Industrial Research and Development Advisory Committee
JET	Joint European Torus
JRC	Joint Research Centre
LEP	Large Electron-Positron Collider
MTH	Major Technological Hazards Program
NEA	Nuclear Energy Agency
NET	Next European Torus
RACE	Research and Development in Advanced Communications Technologies in Europe
RAP	Research Action Program
SPRINT	Strategic Program for Innovation and Technology Transfer
STC	Euratom Scientific and Technical Committee
STD	Science and Technology for Development
STIMULATION	European Cooperation Between Laboratories
STOA	European Parliament Office for Scientific and Technological Options Assessment
TDHS	Technological Developments in the Hydrocarbons Sector
VAMAS	Versailles Project on Advanced Materials and Standards

The research programmes concerning Materials are:

STIMULATION	Stimulation of European Cooperation [see reference 52]
SPRINT	Strategic Program for Innovation and Technology Transfer [see reference 53]
EURAM	European Research on Advanced Materials Program [see reference 46,49,51,52]
BRITE	Basic Research in Industrial Technologies for Europe [see references 46,50,52]
COST	European Cooperation in the Field of Scientific and Technical Research [see reference 46]
EUREKA	European Research Coordination Agency [see reference 46]
VAMAS	Versailles Project on Advanced Materials and Standards [see reference 55]

A short review of the material studies under these programmes is given in reference 2, pp. 36-39; see also (54).

Some of the projects concerned with high temperature materials are as follows:

BRITE:

- Plasma reactor for surface deposition of corrosion-resistant layers
- SiC-reinforced composite turbine wheel with mechanical strength stability at high temperature

EURAM:

- Ceramics intended for future generations of internal combustion engines, especially the adiabatic diesel engine operating at a constant temperature of 1500°C
- Composite materials; synthetic resins with carbon or glass fibers; metal matrix composites
- Mechanical properties and corrosion resistance properties of steels, alloys, and engineering ceramics
- Data bank of characteristics of high-temperature materials
- Processing of monolithic ceramics SiC, Si₃N₄, ZrO₂, Al₂O₃; whisker-fiber composites

EUREKA:

- Precursors for high-performance ceramics by wet chemicals
- Coatings for advanced technology.

Reviews of ceramic research in Europe are given in references (46,48,49, 55-58).

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