JOURNAL OF SOLID STATE CHEMISTRY 96, 108–114 (1992)

The Frontiers of Research in Ceramics Science

JINGKUN GUO

Shanghai Institute of Ceramics, Chinese Academy of Sciences, 1295 Dingxi Road, Shanghai, 200050 China

Received April 4, 1991

To extend the frontiers of research in ceramics science the following tentative trends have been considered: (1) nanostructure ceramics, (2) multiphased composites, and (3) design and tailoring ceramics. The first point concerns methods of processing ceramic materials, such as powder technology, forming technology, and sintering technology, especially at nanoscale. This research depends on both the development of technology and the choice of a scientific direction. The second point is theory. Theoretical investigations should be focused on the surface and grain boundary interface, the relationship between nanostructure and properties, and the compatibility of multiphase systems with expected properties. The third point is design and tailoring of ceramic materials. Ceramics science and related disciplines have been fully utilized to predict the optimal technology, as well as the new properties of ceramics. © 1992 Academic Press, Inc.

Introduction

With the development of high technology, newer and more challenging requirements progressively appear. Beyond metallic, polymeric, and semiconducting materials, more and more attention has been devoted to ceramic materials because of the specificity of their potential properties.

Human civilization is closely related to the development of materials. In a certain sense, ceramics were among the first materials developed but never to the same extent as other materials. Therefore, to speed progress in their development, it is necessary to explore the frontiers of research on ceramic materials.

Before an exploration of these frontiers, however, it is worthwhile to introduce current trends and to explore processing, theory, and design of ceramic materials in more detail.

Current Research Trends in Ceramic Materials

A brief review on this topic is given elsewhere (*1*). The current trends are (1) nanoscale ceramics, (2) multiphase composite ceramics, and (3) tailoring and design of ceramic materials.

1. Nanoscale Ceramics

Ceramics are a type of polycrystalline structure. Most ceramics are obtained by shaping and sintering starting powders. In traditional ceramics, or even in modern advanced ceramics, the grain size at sintering is at the micrometer level; one may speak of microscale ceramics. The present

0022-4596/92 $3.00

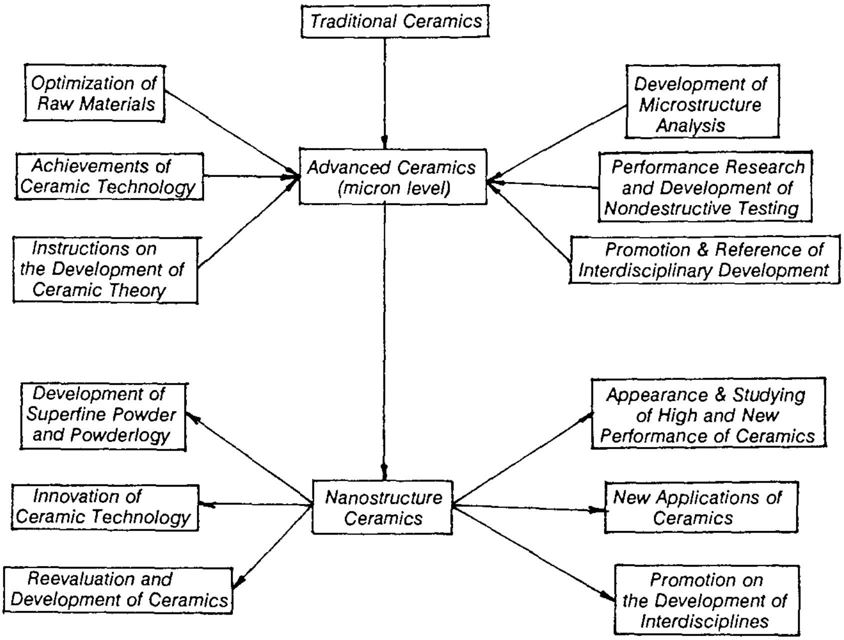

FIG. 1. Three stages of ceramic materials research.

trend is to go from the microscale ceramics to a finer stage, i.e., to the nanoscale level, and to develop nanoscale ceramics (see Fig. 1).

When the concept of nanoscale ceramics was introduced, completely new research fields concerning processing technology, theory, and properties of new ceramic materials appeared. Because nanoscale ceramics have new and better properties, many novel applications were developed. As a result, the application range of ceramic materials could be greatly extended (see Fig. 2). Consequently, research on nanoscale ceramics is an important direction for studying advanced materials in the near future, and it extends the research frontiers in ceramics science.

2. *Multiphase Composite Ceramics*

The microstructure of ceramics can be considered a type of multiphase structure, which consists of a grain phase and a grain boundary phase. In the grain phase, there are three grain combinations: (1) a uniform chemical composition, (2) a different chemical composition, and (3) the formation of different crystals with the same chemical composition. Analyses of the entire development trend reveals that traditional ceramics consists of multicomposition constitutional grains and grain boundaries. Modern advanced ceramics have monoconstitutioned grains, and the grain boundaries are as narrow as possible. Therefore, they can be called monophase ceramics. The current research trend is a transfer from monophase ceramics to multiphase ones. This transformation trend from multiphase to monophase and, later on, to more complex multiphase ceramics illustrates the old rule of spiral development.

The new multiphase ceramics include fiber-reinforced ceramic matrix composites, particle-dispersed multiphase ceramics, and multiphase ceramics composed of

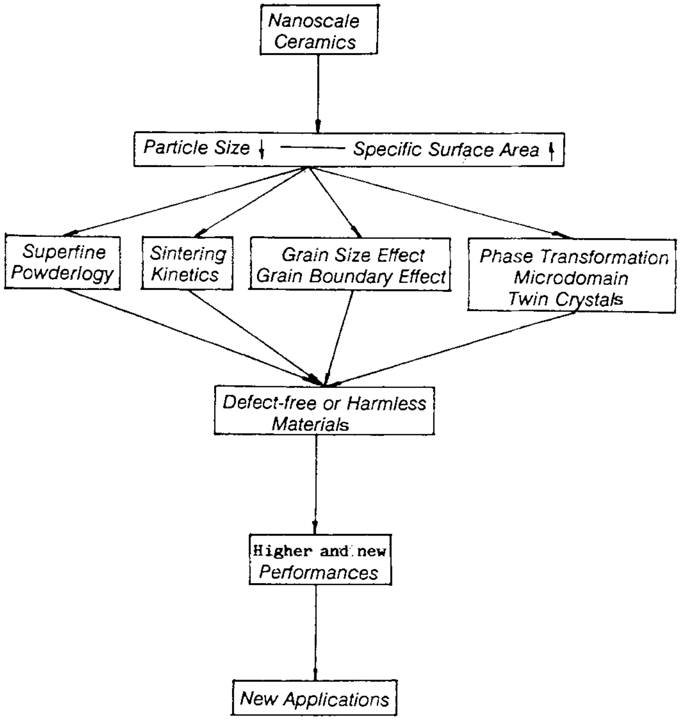

FIG. 2. The research development of nanoscale ceramics.

two different types of crystals. Multiphase ceramics generally have better mechanical properties than corresponding monophase materials. The deficiencies of monophase ceramic materials can be eliminated by designing a multiphase material and giving full play to interactions between individual phases. Thus, ceramic materials with very high performance can finally be obtained. The present development of multiphase ceramics has proved a direction with very strong potential.

Multiphase ceramics are composed not only of inorganic materials, but also of combinations of organic materials to form new inorganic–organic composites. This can allow one to bypass a complex heat treatment process at high temperature, while forming a new type of material that keeps the individual advantages of both ceramics and organic materials. Of course, one must draw from the lessons of the disastrous failures of many investigations on metal–ceramic materials in the past 20 years.

3. Tailoring and Design of Ceramic Materials

Due to the development of the current processing technology of ceramics, the achievements in research on ceramics and the enlightenment from related sciences have led to an improved ability to tailor and design ceramic materials, based on the performance required for a given application. Although this possibility is only at a very primary stage, a trend for the future is obvious and will lead to further achievements. As a result, the investigation of ceramics can be expected to advance from the realm of necessity to that of freedom.

Some Significant Frontiers

On the basis of the abovementioned research trends, a few remarkable frontiers may be identified.

1. Investigation of Processing Technology of Ceramic Materials

The progress in the three current research areas is determined largely by developments in processing technology.

(1). *Powder technology.* The expression ''powder technology'' means that a synthesized powder is able to satisfy the expected requirements for its application. These include particle size and size distribution, particle shape, agglomeration state, chemical compositions and impurities, surface state, and so on. For example, for nanoscale ceramics, the powder grain size must be within $10^{1\pm1}$ nm. Some other properties of the synthesized powder should be designed to satisfy the grain size requirements of the sintered ceramics. Obviously, traditional processing technology cannot fulfill this requirement; thus the link to this traditional methodology must be broken in order to explore new techniques.

Most traditional ceramic powders are prepared by mechanical methods. To synthesize fine powders, chemical processing or combined chemical–physical approaches, such as the chemical precipitation method, hydrothermal processing, controlled hydrolysis of organometallic compounds, plasma or laser chemical reaction method, etc., are often selected. Using such processing technologies, powder with high-purity, superfine, and uniform size distribution and spheroidal particle shape can be successfully synthesized. Of course, all processing approaches have their individual advantages and shortcomings. Therefore, on the one hand, these technologies must be improved and new processing approaches explored. On the other hand, because of the huge surface of the superfine powders, they lead to

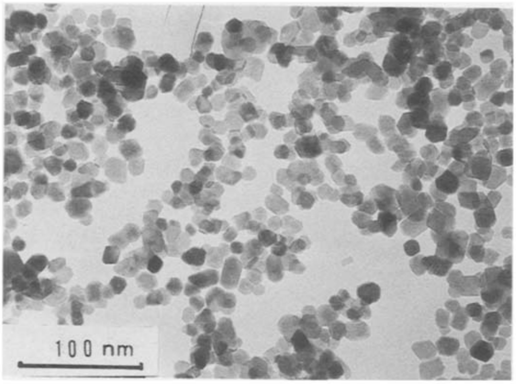

FIG. 3. A TEM micrograph, showing superfine ZrO_2 powder stabilized by Y_2O_3 and synthesized by a coprecipitation method.

a series of new, and so far, unknown changes in chemical and physical properties differing totally from those of ceramic powders prepared by traditional methods. As a result, the development of powder technology, especially the characterization of superfine powders, can be expected to be greatly accelerated.

Figure 3 is a TEM micrograph showing a superfine ZrO_2 powder with a stabilizing Y_2O_3 oxide synthesized by a coprecipitation method. Its average particle size is around 22 nm, and it is of spheroidal shape. Through a suitable and special treatment, the agglomeration of the synthesized powder can be reduced. The powder could be sintered at 1250°C up to a 98% theoretical density. Its sintering temperature is about 400°C lower than that of ZrO_2 powder processed by other means. It fully proves that utilization of superfine powder plays an important role in the revolution in ceramic processing technology.

(2). *Forming technology.* The huge surface of the superfine powder could be of concern in shaping, that is, in obtaining multiphase ceramics from two kinds of different ceramic powder morphologies and densities, uniformly mixed and shaped. Therefore it is impossible to perform the procedure by simply modifying a few technological parameters, and it becomes necessary to design a new technological approach based on powder properties.

In traditional forming technology, one must use a binder and a medium. The superfine particle size results in a sharply increasing number of particles and contact points among particles. The interactions among particles and between particle and medium are strongly enhanced. As a result, the powder agglomeration becomes severe and can affect the sintering process, leading to more closed pores or to fast recrystallization. Weakly combined agglomerations, called "soft agglomerations," favor the process if necessary. Therefore, to improve sintering technology and to develop new approaches to forming, more attention must be paid to the investigation of mechanisms such as the interface effect between particle and medium resulting from their huge surface contact.

In other words, the two types of different powder morphologies involved and the specific gravity problems in the multiphase ceramics can bring about a revolution in ceramic forming technology.

(3). *Sintering technology*. The superfine powder has a very high surface energy. The surface energy, as a driving force during sintering, plays an important role in the densification of ceramics. The fine particle size can reduce the diffusion path of the matter and dramatically increase the number of grains and the possibility of contacts between them. At the same time, it can tremendously accelerate the reaction rate. Thus, it is possible to lower the sintering temperature significantly and to speed the densification rate. To fit these changed superfine powder properties and to prevent too rapid grain growth during sintering, one must explore a few new approaches, such as uniform and fast sintering or the newly developed microwave sintering technology.

In multiphase ceramics, the sintering process is more complex. On one hand, the existence of exotic phases can prevent matter transportation, but on the other hand, it can accelerate interface formation. Therefore, the various sintering processes should be adapted to different multiphase systems.

Briefly, it is an important objective of research on modern ceramic technology to design a new densification process governed by new densification theory.

2. *Theoretical Study of Ceramics*

An unavoidable trend is to develop the theory of ceramics into a more microscopic direction. Apparently, the development of current ceramic technology cannot be completely explained by the theory of modern ceramics. Therefore, there is an urgent need to create a new theory of ceramics to guide the development of technology based on surface and interface, sintering kinetics, grain and grain boundaries, nanoscale structure and properties, compatibility of multiphase systems and properties, relations between properties and structure, predictability, and so on. As mentioned above, in nanoscale powders the large surface and interface not only accelerate the densification process during sintering but also dramatically affect the final properties of the sintered material. It is well known that grain size is closely related to other final properties such as grain boundary. When the grain size is 3–6 nm and the grain boundary thickness is 1–2 nm, the volume of matter is the same at the grain and the grain boundary. Under those conditions, what is the influence of grain size and grain boundary on the material's properties? In general, defects in ceramic materials, such as pores and microcracks, are related to grain size. When defects of the material are minimized to a certain extent, their macroscopic effect on properties should be small and even cancelled. In that case, might it be a realistic approach to fabricate defect-free or harmless-defect ceramics? The effect of the nanostructure of ceramic materials on their properties is very sensitive. Therefore, the study of this nanostructure is an important criterion for technologically designed ceramic materials. An investigation of the compatibility, interface, nanostructure in the multiphase ceramic system, and their relations with properties will result in sintered nanoscale ceramics and multiphase ceramics with more advanced and newer properties. Consequently, the research field could be extended to new high-performance and well-characterized ceramic materials.

In brief, the concepts of nanoscale and multiphase ceramics have broad scientific meaning. Progress in this aspect of research on ceramics could spur development of ceramic technology and provide scientific principles for designing ceramic materials and selecting processing technology.

3. *Design of Ceramic Materials*

The study of ceramic materials is developing from an art to a science under the influence of modern scientific theory. Progress in the past decades has been encouraging. With the improvement of ceramics and ceramic technology, tailoring and designing ceramic materials have advanced progressively the past few years. The accumulation of a greater number of phase diagrams with better accuracy provides an abundant and solid basis for knowledge of the composition and of the relationships between microstructure and properties. In deciding the design of the composition and microstructure of the material, the choice of the optimal technology is important for anticipating the properties and predicting the best materials for a specific application. The desired material can be obtained by optimizing the technological processing.

To fabricate a ceramic with high strength and good creep resistance at high temperature, Si_3N_4 ceramics with stronger potential properties were selected as a suitable candidate. Si_3N_4 ceramic is a covalent compound and its diffusion coefficient is low; therefore, if we wish to satisfy the densification requirement during a dissolving–diffusing–precipitating process, it is necessary to use additives that form a liquid phase at sintering temperature. However, a liquid phase at low temperature can reduce the high temperature strength and high temperature creep resistance of the material. The key to designing the material is to solve this contradiction. First, based on the phase diagram, the composition range leading to a liquid

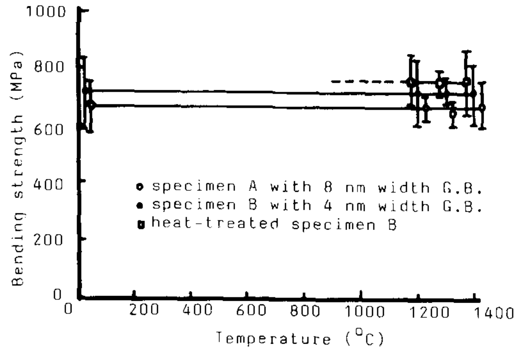

FIG. 4. The dependence of bending strength on temperature of $YL\text{–}Si_3N_4$ ceramics with different GB widths.

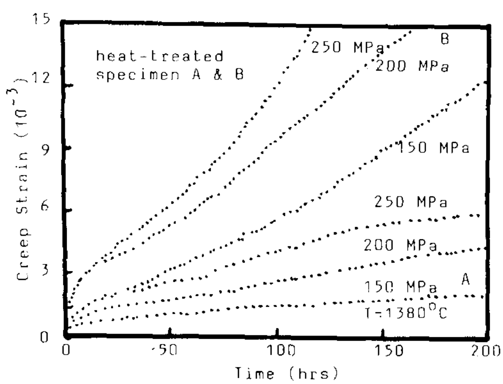

FIG. 5. The dependence of high temperature creep resistance of $YL\text{–}Si_3N_4$ ceramics on different GB widths.

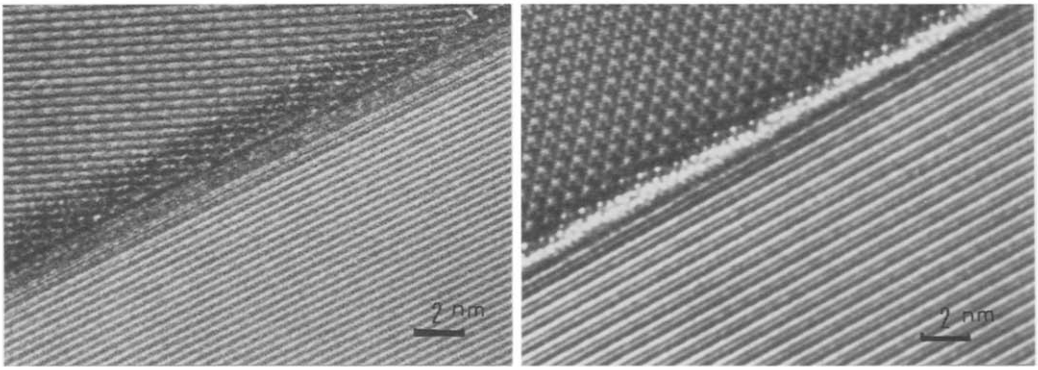

FIG. 6. HR-TEM picture of YL–Si_3N_4 ceramics with different GB widths.

phase under Si_3N_4 sintering conditions should be chosen, and the constitution of the grain boundary phase of Si_3N_4 ceramics defined to give rise to heat treatment suitable for crystallization. Second, the microstructure of the material, including mainly Si_3N_4 crystals, the controlled range of grain size, the preliminary and crystallized composition of matter at the grain boundary, and the thickness of grain boundary, should be designed. Finally, the processing technique should be optimized to satisfy the above requirements. Designed by these three principles, hot pressed Si_3N_4 ceramics with Y_2O_3 and La_2O_3 additives appear to be quite successful in practice (*2, 3*). Figure 4 shows the dependence of bending strength on temperature of hot pressed Si_3N_4 ceramics with different grain boundary (GB) widths. Figure 5 illustrates the dependence of high temperature creep behavior vs time of YL–Si_3N_4 ceramics with different GB widths. Figure 6 gives HR-TEM pictures of YL–Si_3N_4 ceramics with various GB sizes.

Nanoscale ceramics is a general approach to developing materials at new and higher levels. It broadens the research fields for designing ceramic materials. Multiphase composite ceramics include fiber (or whisker) reinforced ceramics and particle dispersion ceramics. The chemical and physical compatibility of the multiphase system, characterization of different phases, and optimized process technology can be utilized to design ceramic–organic and ceramic–metallic composites. Thus, one may elaborate on multiphase composite ceramics in order to satisfy different practical requirements.

Conclusion

In order to raise ceramic research, the theoretical approach and the design of ceramic materials, to a more advanced level, the frontiers of research in ceramics science, such as nanoscale ceramics, multiphase composites, and the design and tailoring of ceramic materials, should be explored simultaneously. Because frontiers of research in ceramics science not only depend on practical achievements in ceramics elaboration, but also benefit from developments in related fields, the scope of investigations should be extended. Therefore, it is a historical target for ceramic scientists to study their materials in going from the realm of necessity to that of freedom.

References

1. J. K. GUO, to be published.
2. Y. R. XU *et al.*, *Kexue Tongbao* (*Science Bulletin, China*), **33**(10), 832 (1988).
3. Y. R. XU, X. R. FU, AND D. S. YAN (T. S. YEN), *Physica B* **150**, 276 (1988).