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CERAMIC MATERIALS

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It is appropriate to have ceramic materials represented in a symposium on Technology Forecast for 1980. In addition to their own development, ceramic materials will play a significant role in many of the technological developments of the next decade. This role is primarily due to their potentially greater high temperature stability, both chemically and mechanically, although their high strength/density and modulus of elasticity/density ratios make them of general mechanical interest. Ceramics also are part of the exciting developments in the area of optical, electronic and magnetic devices exemplified by solid state electronics. These ceramic materials will be covered later by Dr. Bruce Hannay. Before going any further, however, let us take a few moments to establish communications between ourselves to make sure that we are thinking similarly in regard to the word ceramics and its relationships. My past experience indicates that there is a problem of semantics.

Early usage of the word ceramics included dinnerware, sanitaryware, porcelain, wall tile--all referred to as whitewares; refractories or high temperature furnace components, structural clay products, glass, porcelain enamels, and--of course--pottery. These still constitute the major part of the ceramic industry. The traditional ceramic industries are thus product oriented; they produce the material as a finished product that is used as a unit without further processing by the user. By comparison, the metals industry was, and is, essentially materials oriented--that is, it produces materials that are processed by the using industries to produce some kind of product, all the way from cans to bridges. Metals were "handbook materials" that the designer automatically considered and used. If necessary, designs were adjusted to fit the listed property values without loss of performance. The procedure followed in selecting a material is shown in Fig. 1.[1]

This procedure was satisfactory until handbook materials with desired property and behavior characteristics, particularly for hostile environments, were no longer available. Consequently, there is now great interest in ceramic materials because of their potential promise of filling some of the gaps. In the following discussion, however, I will ignore the traditional ceramic product lines and devote my time to the ceramic materials aspects which really are of primary interest and importance for engineering utilization considerations.

Again, in order to avoid any confusion, let us take a few more moments to present an overall view of the types and nature of materials to show where ceramic materials fit into the materials spectrum. All processed materials used by engineers are universally divided on a broad basis in terms of general chemical and physical characteristics as shown in Fig. 2. The principal and most differentiating feature is the type of chemical bonding or the electronic structure. Metallic materials or metals are self-identifying. Organic materials or polymers are covalent bonded materials that consist of some combination of essentially C, O, H, N and S. Ceramic (non-metallic inorganic) materials or ceramics are ionic-covalent bonded with the latter type of bonding ranging from essentially none to all. There are several other interesting relationships shown in the figure that should be mentioned. Because of the nature of bonding, the metals are primarily represented by elements, and the polymers and ceramics, by compounds. Also, the materials with highly metallic and ionic character (metals and some ceramics) are crystalline whereas those with highly covalent character (polymers and some ceramics) are amorphous or glassy. Composite materials or composites are mixtures of any two types of identifiable materials in which the continuous phase can be any one of the three types of materials.

Materials can also be classified or discussed on the basis of the three broad property categories of mechanical, optical, and electrical-magnetic. As mentioned, the ceramic electronic materials will be covered later. I will thus devote my discussion to ceramic materials that are being utilized for their mechanical properties which are of primary concern for structural applications under all environmental conditions.

The desirable mechanical characteristics of ceramics have already been mentioned. Unfortunately, these have not been fully realized in practical applications because of the undesirable characteristics of brittleness, and poor mechanical and thermal toughness, i.e. low mechanical shock and thermal shock resistance. These characteristics are associated with a lack of ductility and result in a scatter of data for most property measurements. This has been equated to a "lack of reliability" and has resulted in a loss of confidence in ceramic materials on the part of designers. Nevertheless, it is well-recognized that many engineering designs are limited in unfriendly environments because of deficiencies of presently available and accepted structural materials. The desirable and potentially available characteristics of ceramics are sufficiently attractive so that it becomes worthwhile to make continued efforts to circumvent their undesirable characteristics for structural applications. It is expected that a substantial effort will be made in this direction during the NEXT DECADE which should result in an improvement of engineering ceramic materials and lead to their increased use.

This effort will be dependent upon developing and controlling the desired character of the material. What is character? In an ultimate and idealistic sense, it is a complete description of the material and can be represented by the formula

$$C_T = C_A + C_\mu + C_M$$

where C_T is total character, C_A is atomic and electronic structure, (ideal and defect), C_μ is microstructure, and C_M is macrostructure (size and shape).[2] Character is important because the properties of a material are dependent upon certain features of its character. One of the objectives of materials science is to identify the character features upon which a given property is dependent. The character, of course, is determined in processing. Control of this character involves understanding every step of the processing sequence, starting with the raw materials, and their affect on the character of the material. These interrelationships are shown in Fig. 3.[3] It can be seen that a producer makes a material with a certain character and that this character determines the properties of the material; the producer does not simply make a material with certain properties. The full acceptance of this philosophy and realization of the relationships will lead to a scientific approach. Probably the most significant development in the NEXT DECADE within the field of ceramic materials will be a giant step toward the establishment of a science of ceramic processing.

It is important to explore the practical significance of the development of such an approach. Controlled and scientific processing will reduce variability which occurs in the character of a material during processing and will allow the achievement of specific character features. The principal return of reduced variability will be a reduction of the scatter of data because the scatter is at least partially due to variability of character from piece to piece. This achievement will automatically result in optimization of properties, will lead to greater automation in processing, and will in turn increase the confidence level on the part of the designer. The capability of achieving specific character features will result in the making of engineered characters and thus attaining improved and desired properties.

Similar developments are also in progress within the fields of metallic and organic materials. As a result probably one of the most significant developments in the NEXT DECADE within the whole field of materials will be the systems approach to materials selection.[1] As shown in Fig. 4, character is the core of this approach. A systems approach as this one can be computerized. The analysis will indicate the material, whatever it may be, which will have the necessary properties and which can be processed to produce a desired shape "at-a-price." This approach is of value even if a material with a specified character may not actually be available, because it becomes a means for providing ideas for materials research and for designing a character for the purpose of optimizing certain properties and behavior.

Ecological problems associated with pollution should also be given some attention for materials are not exempt from criticism, and because engineers and the technological industries are being criticized. First, engineering is defined as the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize economically the materials and forces of nature for the benefits of mankind. The engineer has done a good job in benefiting mankind as evidenced by the wealth of our country and a standard of living which is the highest in the world. But, up until now the phrase "for the benefit of mankind" was interpreted essentially from the viewpoint of the economic production of the product itself with a minimum of attention towards pollution of the atmosphere, water systems and the countryside and towards the problems arising on disposal of discarded products. Obviously, these approaches were established when such problems were not critical, when the population density was low. With our population explosion, however, this is no longer the case. Thus, it is inevitable that during the NEXT DECADE more attention will be paid to this area which will undoubtedly lead to some modifications of processing and design of materials and products.

Now, let us look at a few specific expected developments in the character of ceramic materials in terms of structural applications. In this vein there is more interest in oxide materials, e.g. Al_2O_3, MgO, BeO, $MgAl_2O_4$, and stabilized ZrO_2, which potentially are most interesting because of their greater resistance to hostile environments. There are, however, applications for carbides, borides and graphite because they are normally stronger and maintain their strength, in some cases, as high as 2500°C. But, in all cases, it is necessary to combat the main undesirable characteristics of brittleness and poor toughness or shock resistance, both mechanical and thermal. These characteristics are associated with relatively easy crack nucleation and crack propagation. Possible solutions or ways of minimizing crack nucleation are increasing the strength and reducing non-uniformity or flaws that act as "stress raisers" or that already are crack nuclei. Crack propagation can be minimized by development of energy dissipating or absorbing features of character.

The question then arises as to what features of character are critical in controlling strength. Experiments have indicated that strength increases with an increase in density or decrease in porosity, e.g. as shown in Fig. 5 for Al_2O_3 bodies at room temperature and 750°C.[4] Experiments also show that strength normally increases with decrease in grain size. It is then logical to conclude that a desirable character would be one of theoretical density and fine grain size. Two examples of microstructures of polished 99+% MgO specimens are shown in Fig. 6.[5] The one on the left had a higher compressive strength. The state-of-the-art in sintering is such that the usual ceramic body is opaque because it generally has a minimum of about 2-3% porosity, as seen on the right side of the figure. If theoretical density is achieved as it was for the specimen on the left by a special hot-pressing technique, transparency results since MgO crystals are isotropic; the microstructure is then similar to that for a metal. In looking at the two photomicrographs, however, there is no visible difference in the grain boundaries. But, electron scanning microscope examinations of fractured surfaces (Fig. 7) do show differences. The one on the left of the transparent piece shows essentially an intergranular fracture, whereas the one of the opaque piece on the right is largely transgranular in nature suggesting stronger grain boundaries. The specimen on the right shows ductility as low as 800°C whereas the one of the left does not until 1200°C because of dissipation of energy at weaker grain boundaries.[6] It would be expected also that the strength of the theoretically dense specimen would be higher at room temperature with stronger grain boundaries. Strong grain boundaries must thus be added as a desired character feature. Presence of impurities and non-uniformity of microstructure features are considered to be contributing factors to an overall weakening of grain boundaries resulting in poor resistance to crack nucleation. Considerable interest now exists in developing processing techniques for the preparation of synthetic raw materials. The objectives include the control of purity, mixing on an atomic level, and the physical nature of the starting materials. Such techniques as freeze-drying and coprecipitation are currently of great interest. It is expected, therefore, that in the NEXT DECADE many unusual processing techniques and procedures will be explored and developed to achieve ceramic materials with the desired character of theoretical density, small uniform grain size, and strong grain boundaries.

It is also evident that the electron scanning microscope is an extraordinary instrument for observing characteristics of microstructures of ceramic materials. This microscope should contribute more to the characterization of ceramic materials than any other type of microscope that has been available to date. It is predicted that in the NEXT DECADE the electron scanning microscope will play as significant a role in the development of ceramic science as the metallographic microscope did in the development of physical metallurgy many years ago.

The problem of understanding and controlling crack propagation is considerably more complex. The character of the material must provide some energy absorbing feature that will tend to dissipate the energy of the propagating crack and thus blunt its growth. The presence of such a feature may also delay or retard the appearance of a crack nucleus. A uniform, stable low energy structure of a single phase principally ionic type of ceramic material is inherently brittle because of the absence of such character features. To date, the most promising approaches have been those of composites or unusual microstructures which are thermodynamically unstable. These structures are potentially effective because a propagating crack can be blunted by the ductile metallic phase of a composite, if present, or can branch and dissipate its energy by travellong along the interfaces between the composite phases.

Successful composites have been made with metal and organic matrices using ceramic fibers, e.g. Al_2O_3 ZrO_2, SiO_2, SiC. These have been successful because of the higher strength and stiffness of the fiber relative to the matrix. Work on development of ceramic fibers should thus continue. At present, however, there is no state-of-the-art in the area of ceramic matrix composites because of the lesser stiffness of metallic and polymer fibers. A promising approach has been the use of ceramic fibers in a ceramic matrix, e.g. C in C and ZrO_2 in ZrO_2, as a means of gaining strength. Nevertheless, there is still interest in composites with metallic fibers or whiskers because of the possibility of gaining some structural integrity or toughness through the development of pseudo-ductility, i.e. prevention of complete failure upon the appearance of cracks. Since at present it appears to be the only possible way to achieve shock resistance, the NEXT DECADE will see activity in these types of composites. As a result, a state-of-the-art should develop in composites with ceramic matrices. Unusual processing techniques will also be explored in an effort to obtain unusual and thermodynamically unstable microstructures which may provide energy-dissipating features; these will be largely exploratory in nature.

In summary, the following technological forecasts relating to ceramic materials are made for the NEXT DECADE:

1. Improved and more reliable ceramic materials because of extensive processing studies, resulting in their emergence as accepted engineering materials because of greater confidence on the part of designers and engineers.

2. Substantial progress towards the establishment of a science of ceramic processing which will enable the development and control of desired characters.

3. Systems analysis approach to materials selection based on character as the core, and the establishment of the character of materials as a means of communication between the producers and users of materials.

4. Greater concern over pollution problems will be a factor in modifying production procedures.

5. Considerable progress toward realizing theoretically dense ceramic materials with very fine uniform grain size and strong grain boundaries resulting in stronger and more reliable ceramic materials, and

in materials with greater optical transmission capabilities.

6. Improved characterization of ceramic materials, particularly because of the availability of the electron scanning microscope.

7. Development of a state-of-the-art in composites with ceramic matrices resulting in reliable materials with greater structural integrity and toughness, and thus mechanical and thermal shock resistance.

8. The continued improvement of the technology of composites utilizing ceramic fibers or whiskers.

9. Exploratory studies on the achievement of unusual and thermodynamically unstable microstructures designed to increase resistance to crack propagation.

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FIGURE CAPTIONS

Fig. 1. Normally used materials systems analysis as a basis for selecting an engineering material.[1]

Fig. 2. Relationships between the three types of engineering materials.

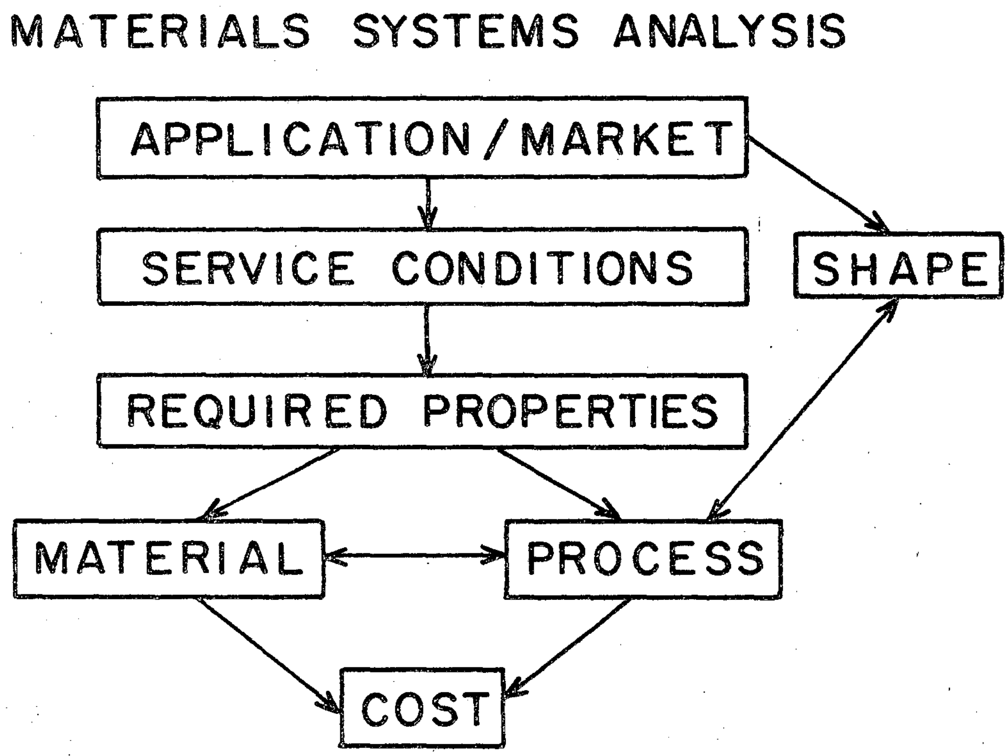
Fig. 3. Indication of dependence of character of a material on the processing steps; its character determines the properties of a material.[3]

Fig. 4. Materials systems analysis using character of material as a basis for selecting an engineering material.[1]

Fig. 5. The effect of porosity on transverse strength of alumina.[4]

Fig. 6. Transparent and opaque polycrystalline MgO with corresponding microstructures.[5]

Fig. 7. Electron scanning micrographs of fractured surfaces of transparent (left) and opaque (right) polycrystalline MgO.[6]



XBL 6912-6707

Fig. 1

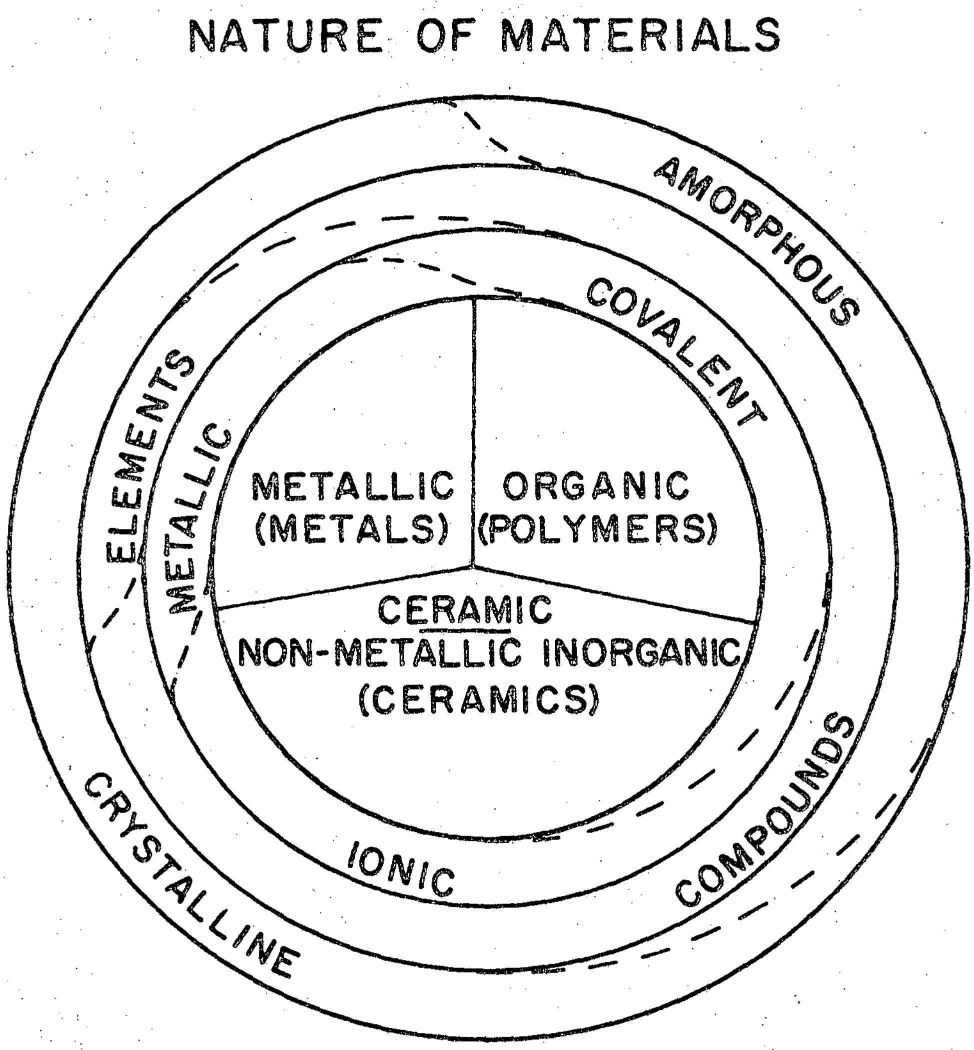


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Fig. 2

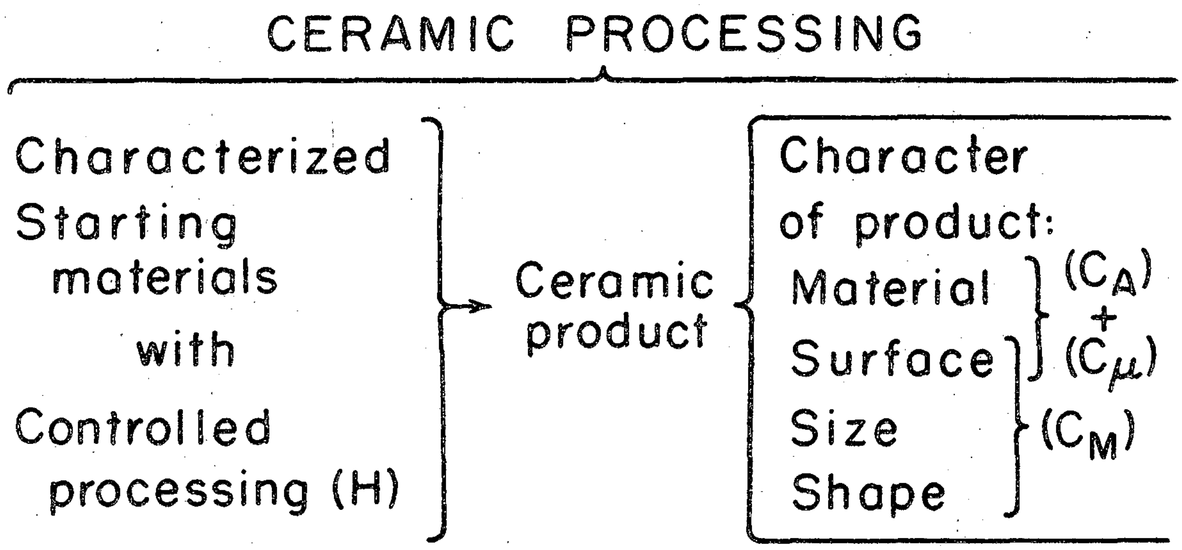

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Fig. 3

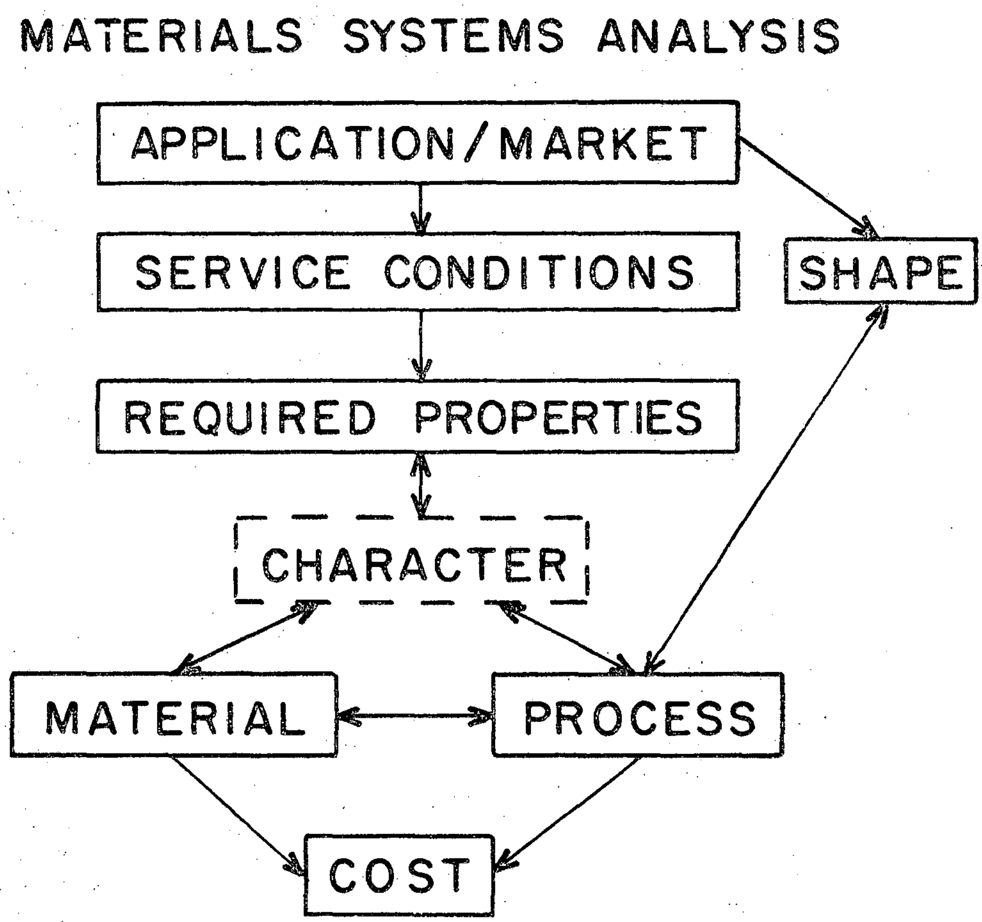

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Fig. 4

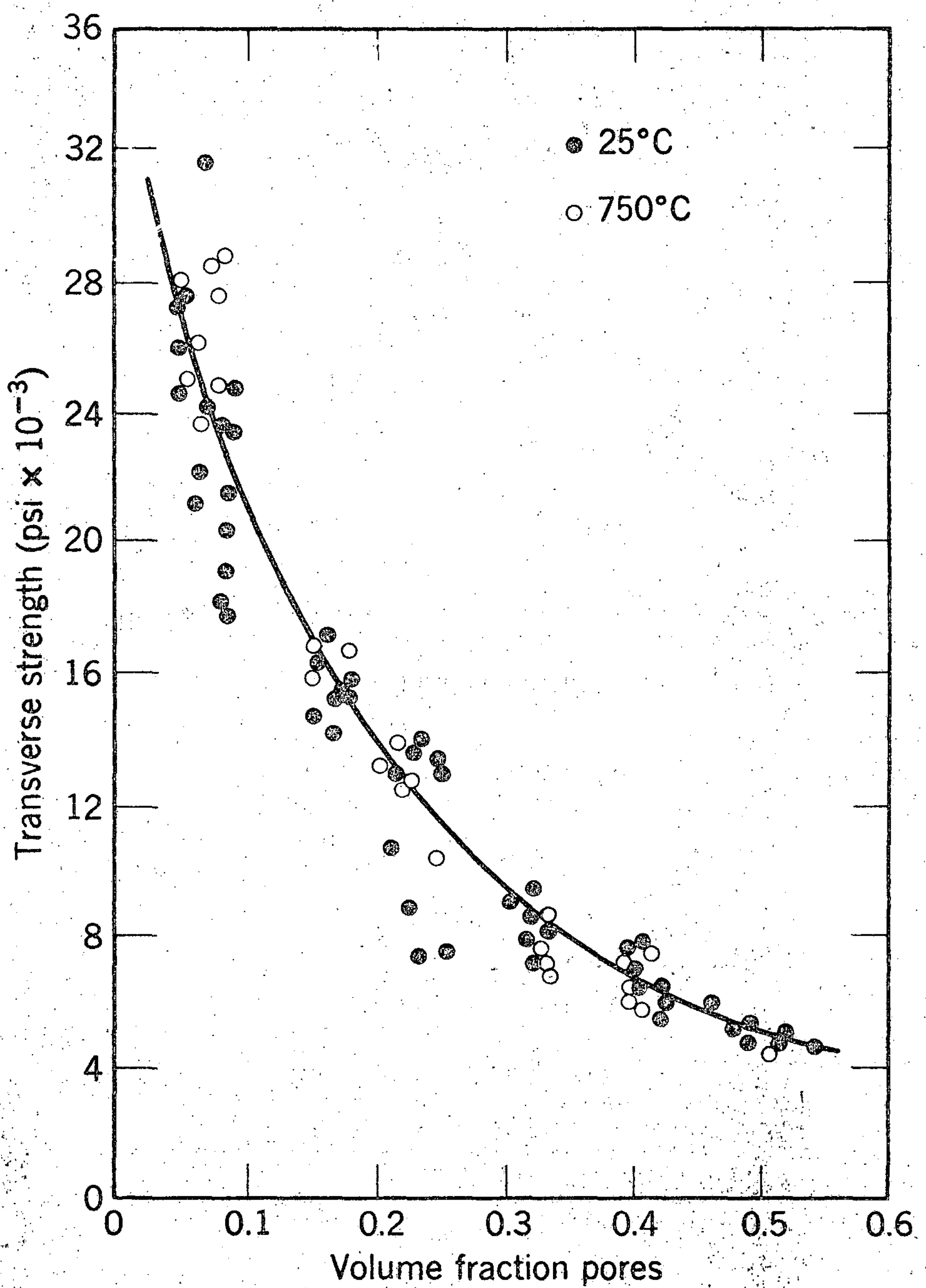

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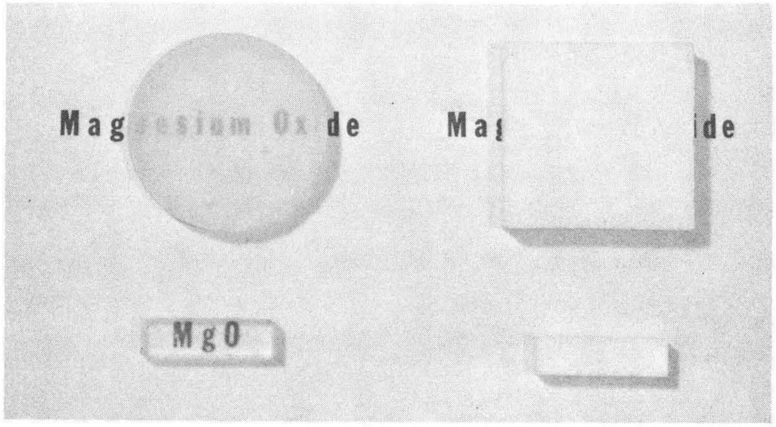
Fig. 5



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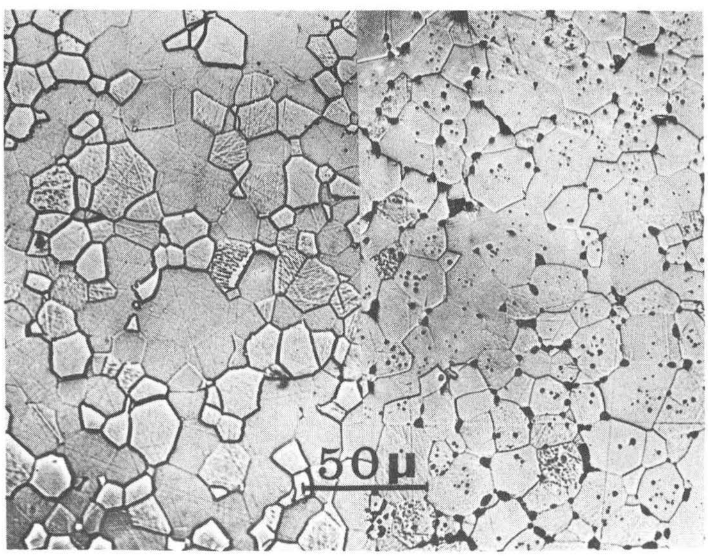

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Fig. 6

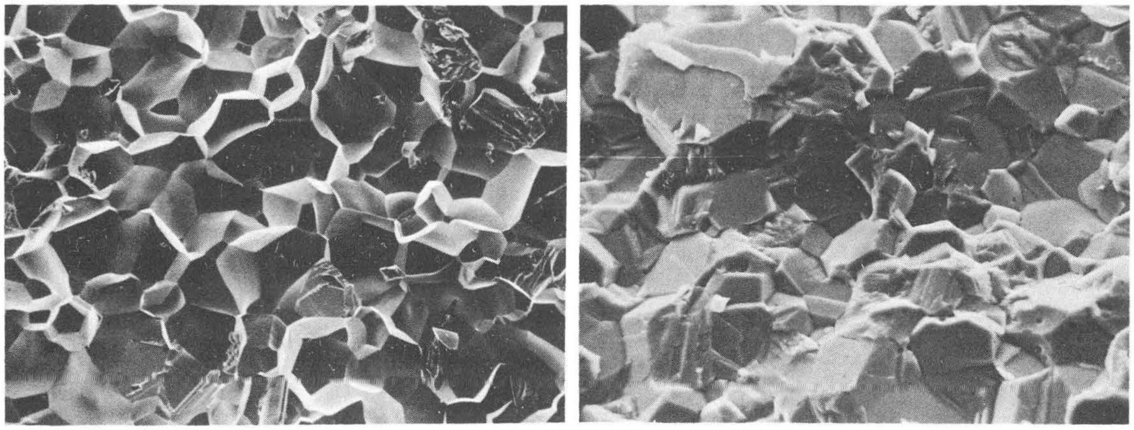

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Fig. 7