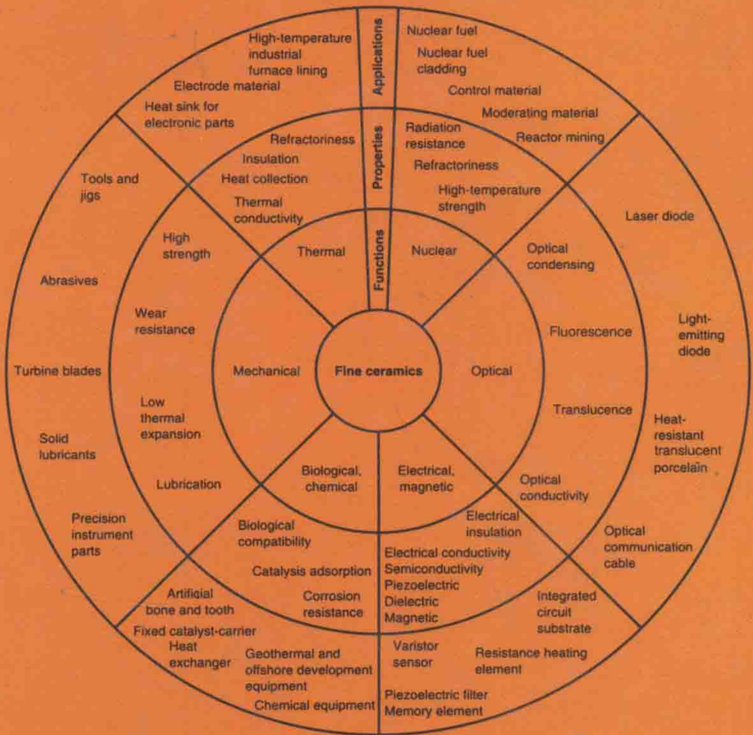
WHAT EVERY ENGINEER SHOULD KNOW ABOUT

CERAMICS



Solomon Musikant

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WHAT EVERY ENGINEER SHOULD KNOW ABOUT
CERAMICS

WHAT EVERY ENGINEER SHOULD KNOW

A Series

Editor

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Additional volumes in preparation

This book is dedicated to that human
who made the first ceramic molded figurine
24,000 years ago

Preface

The purpose of this volume is to provide an overview of the rapidly advancing class of materials known as ceramics. Amazingly, human-made ceramic articles 24,000 years old are known, yet the technology of ceramics is a rapidly developing applied science in today's world. In fact there is keen competition among the leading industrial nations to exploit this science to the fullest.

The modern engineer or scientist encounters new developments daily. It is virtually impossible to be fully knowledgeable in even the limited areas that impact on one's individual field of endeavor. However, any technologist who has to deal with materials needs to be at least conversant with what is going on in the discipline of engineering ceramics.

Revolutions are taking place in which advanced ceramics play critical roles. A few such areas include the Space Shuttle, superconductivity, nuclear reactors, advanced gas turbines and reciprocating engines for energy conservation, integrated circuits, the laser, advanced optics, fiber optics, and biomedical applications. Each of these application areas represents truly amazing changes in the modern world.

This volume reviews the evolution of the ceramic technology and the early influences leading to today's worldwide interest in this arena. Although not intended to be a design manual, property tabulations and discussions of the major issues leading to successful applications are provided. The subjects covered include traditional ceramics, the new ceramics, ceramic processing, structural design considerations, the concept of fracture toughness (a central issue in ceramics), joining of ceramics, nondestructive testing and its importance, ceramic cutting tools and their implications, superconductive ceramics, advanced automotive ceramics, and carbon-carbon composites.

The structure of the ceramic crystal is complex and leads to many different forms. When one considers the number of atom types and arrangements that can be synthesized into ceramic bodies, it is easy to appreciate the fact that there is an infinite number of possibilities for the properties of such structures. That is why the developments in ceramics are leading to astounding discoveries and accomplishments. In the future, more and more variables will be discovered, studied, and applied, making possible even more revolutionary and useful applications.

Solomon Musikant

About the Author

Solomon Musikant is President, TransCon Technologies, Inc., Paoli, Pennsylvania. He is also Adjunct Professor in the Graduate Engineering School at Villanova University, Villanova, Pennsylvania. Previously, Dr. Musikant served as Program Manager for Advanced Materials, General Electric Co., Astro Space Division, where he led research and development of advanced materials for spacecraft (1968-1990). The author or editor of over 60 publications, including *Optical Materials: An Introduction to Selection and Application* and *Optical Materials: A Series of Advances, Volume 1* (both titles, Marcel Dekker, Inc.), Dr. Musikant holds six U.S. patents for glass and ceramic processes and applications. A Fellow and Director of SPIE, The International Society for Optical Engineering, he received the B.S. degree in mechanical engineering from the Cooper Union Institute of Technology, New York, New York, M.S. degree in metallurgy from the Stevens Institute of Technology, Hoboken, New Jersey, and Ph.D. degree (1967) in materials science from Lehigh University, Bethlehem, Pennsylvania.

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1

Ceramics Fundamentals

Ceramics is commonly defined* as the art that deals with the design and fabrication of objects made from fired clay. An ancient piece of utilitarian earthenware fabricated about 1200 B.C. is shown in Figure 1.1; Figure 1.2 shows modern porcelain figurines of great delicacy and beauty. These products are about 3200 years apart in time but not so far apart in the principles of their fabrication or in the degree to which they are appreciated. All types of earthenware, stoneware, and porcelain are included in the term "ceramics." *Porcelain* refers to wares that are fired at high temperatures and are translucent, while *stoneware* and *earthenware,* such as terra-cotta, are fired at successively lower temperatures and are opaque.

More specifically, *ceramic* is defined as any of various hard, brittle, heat- and corrosion-resistant materials made by firing clay or other minerals and consisting of one or more metals in combination with one or more nonmetals, usually including oxygen. This definition must include not only pottery, but refractories (i.e., high-

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**American Heritage Dictionary* (Boston: Houghton Mifflin Co., 1978).

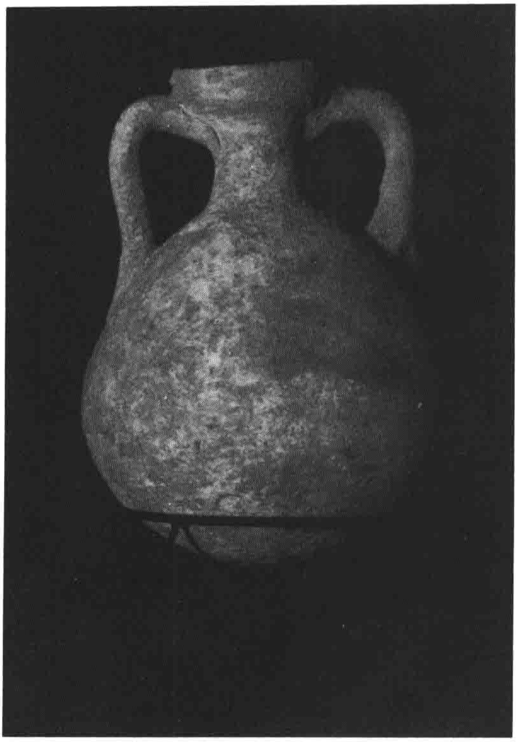

Figure 1.1 Ancient earthenware jug, approximately 1200 BC, Israel. (Photograph by S. Musikant.)

temperature resisting), structural clay products, ceramic coatings, abrasives, glass, glass-ceramics, and certain types of electronic compounds. In fact, a material such as silicon carbide, in which both the silicon and the carbon atoms have some metallic properties, is still considered a ceramic, although here there is some overlap with the definition of a semiconductor.

Glass is a special case. Although we have included glass in the definition of ceramic, the major distinction is that glass is an amorphous material, whereas ceramics are primarily crystalline in nature.

Figure 1.2 Porcelains modeled by Arno Malinowski for the Royal Copenhagen Porcelain Manufactory. Figures, left to right: Asia-Europe, Africa, America, Australia. These important porcelains mark a departure from the forms of earlier porcelain ware. (Courtesy of the Cooper-Hewitt Museum of Design, Smithsonian Institution.) From "Ceramic Masterpieces" W. David Kingery and Pamela B. Vandiver, Free Press 1986.

However, most common ceramics have glassy phases incorporated in their microstructures. Glass-ceramics are another class of materials in which very small ceramic crystals are incorporated in a matrix of glass. The tiny crystallites impart desirable mechanical and thermostructural properties. Pyroceram is an example of a glass-ceramic.

Magnesium oxide (MgO) is an example of a simple oxide ceramic that is used as a high-temperature insulation in the form of blocks with some structural strength (i.e., a refractory) and that has a melting point of 2800 °C (5072 °F). It is a commonly used material for high-temperature industrial furnaces.

EVOLUTION OF THE CERAMIC TECHNOLOGY

The earliest known clay figures have been dated at about 22,000 B.C. Figure 1.3 illustrates some of the known history of ceramic art. As can be seen, every age contributed to the body of ceramic know-

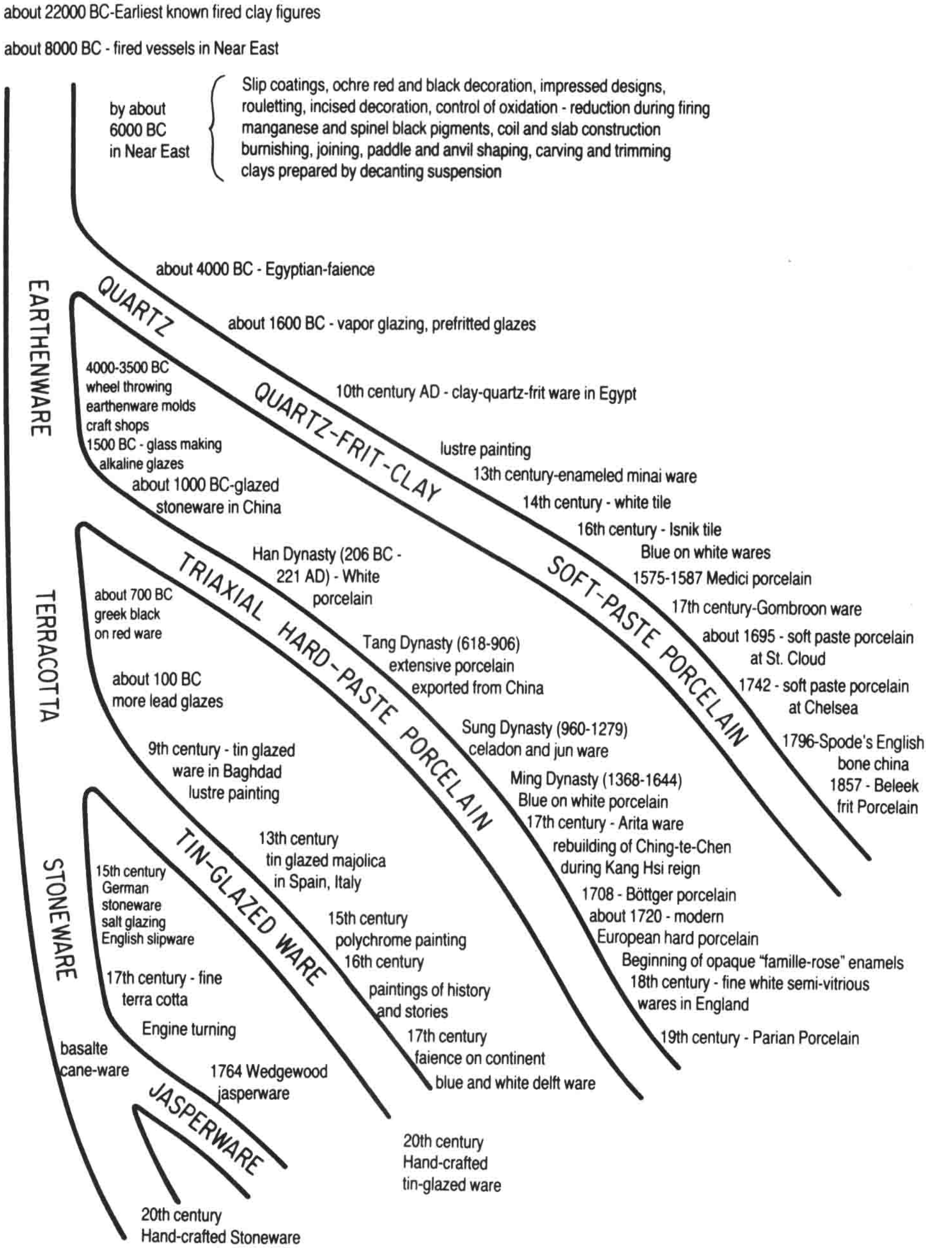

Figure 1.3 The flow of ceramic history illustrates the mainstreams of earthenware, terra-cotta, and stoneware; to "triaxial" hard-paste porcelain; of quartz-based bodies; and of tin-glazed ware. Some important shaping and decorative techniques are illustrated, but the diagram is far from complete. From "Ceramic Masterpieces" W. David Kingery and Pamela B. Vandiver, Free Press 1986.

ledge. This storehouse of information is culminating in today's rapid technological developments in the field of ceramic materials.

Like many human endeavors, ceramics is an art whose beginnings are shrouded in the misty past, probably before invention of the written word. This is not a unique situation because it is easy to say the same thing about many of our "new" and revolutionary technologies. Examples include weaving, agriculture, metallurgy, the use of fire, mathematics, astronomy, weather forecasting, navigation, the sail (aerodynamics), mechanics (the lever, the wedge, the wheel, and the inclined plane), and as already stated, ceramics. The word itself comes from the Greek *keramos* pottery.

The industrial revolution was made possible by advanced furnaces and heat engines, and ceramic materials were essential for thermal insulation of the various types of furnaces and engines. In England, Wedgewood developed mass production techniques for ceramics that put useful and beautiful ceramic dishes within the reach of many. During the nineteenth and twentieth centuries the scientific understanding and manufacturing arts for the production of ceramic articles reached a high degree of sophistication. There became available a wide variety of new types of building materials with superior durability, strength, and other properties. These materials included brick, tile piping for drainage systems and roofing, sanitary ware, which was a primary factor in the development of public sanitation, and refractory (high-temperature) insulation materials, which served as furnace linings for the glass, steel, and other industries that depended on high-temperature processes. Rock wool is an early example of a ceramic fiber used to insulate buildings and appliances.

The raw materials for most, if not all, of these products came from mines and quarries, and these raw ingredients were prepared for the thermal processes needed to convert them to useful articles by crushing, washing, sieving, and mixing appropriate formulations. Usually, these naturally found materials were not pure, and the formulas had to take into account the small fractions of naturally occurring and often variable impurities and minor fractions.

Dielectric (electrically insulating) materials were important as the electrical and electronic technologies matured during the present