2 Classification of Ceramics

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2.1 Monolithic Ceramics (Single Crystal, Sintered Body, Glass, etc.)

Ceramics are non-metallic inorganic solids. Ceramics are classified into “monolithic ceramics” composed of a single chemical compound and “composite ceramics” composed of multiple chemical compounds.

Monolithic ceramics that are typically composed of a single chemical compound are explained below. Crystals represented by precious stones such as diamonds, potteries and porcelains are frequently produced by high temperature firing processes (Note 2.1) and glasses are classified as monolithic ceramics (Fig. 2.1). This classification is based on atomic arrangement and structure, and it is intended for the understanding of ceramics.

2.1.1 Crystalline Materials and Amorphous Materials

Ceramics consist of atoms that are bonded together. Ceramics can be roughly classified into two types depending on the arrangement of atoms that constitute the particular substance.

1. Crystalline solid: a solid in which atoms are arranged periodically and in a certain order throughout the material.
2. Amorphous (non-crystalline solid): a solid in which atomic arrangement does not have long-range order.

According to the examples described above, precious stones, potteries and porcelains are classified as “crystalline solids” and glass is classified as “amorphous.” Amorphous solids have homogeneous qualities, but the atomic arrangement is irregular, unlike crystalline solids in which atoms are arranged regularly or periodic (Fig. 2.2). However, the arrangements are regular at certain distances depending upon the atoms, but this range is limited (this type of arrangement is called “short-range order.”)

It is actually very difficult to tell if a ceramic is classified as crystalline solid or glass. For example, some watch faces are covered by a transparent alumina crystal instead of glass because alumina is resistant to scratches, and it is difficult to distinguish between the two materials using the naked eye. Is there any method in which to distinguish between crystalline solids from amorphous solids? Generally, X-rays, which have wavelengths much shorter than normal light, is utilized for this determination. If the atoms are arranged regularly in repeating atomic planes, reflected X-rays interact with each other, causing a strong reflection facing toward a certain direction. Strong reflections are not observed in amorphous solids because the atoms are arranged irregularly.

2.1.2 Crystalline Solid: Single Crystal and Polycrystals

Monolithic ceramics are divided into “crystalline solids” and “amorphous solids,” as explained above. “Crystalline solids” can be subdivided into “single crystals” and “polycrystals (more commonly known as polycrystalline materials)” (Fig. 2.2).

1. Single crystals: solids in which atoms are arranged periodically from one end of the material to the other end and where grain boundaries are not present.
2. Polycrystals: a crystalline solid consisting of many grains, where the orientation of one grain is usually different from that of the adjacent grain.

In single crystals, atoms are arranged periodically throughout the solid, but the properties may vary depending on the direction of the arrangement (anisotropy). “Cleavage,” or cleaving uniformly in a particular crystalline direction, is observed in a number of single crystals such as in diamonds.

Note 2.1 Technically speaking, potteries and porcelains usually contain several compounds and glass. But they were explained in this manner because ceramic materials for electronic parts, etc. are made from a single compound, although they are usually made by a similar method using a refined material.

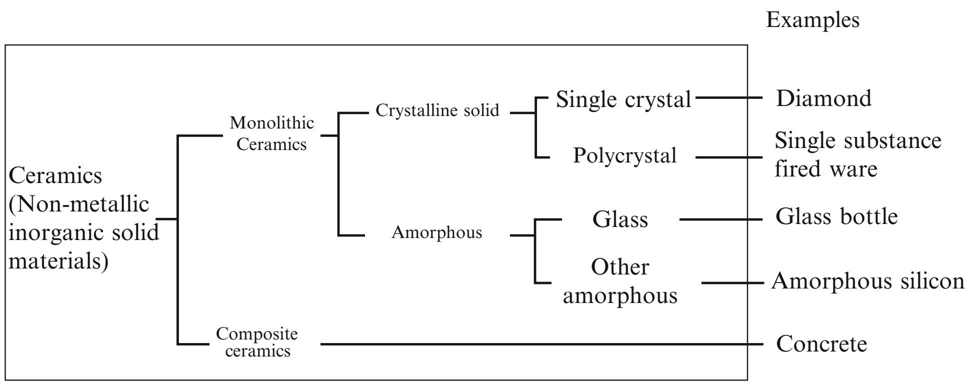

Fig. 2.1 Classification of ceramics

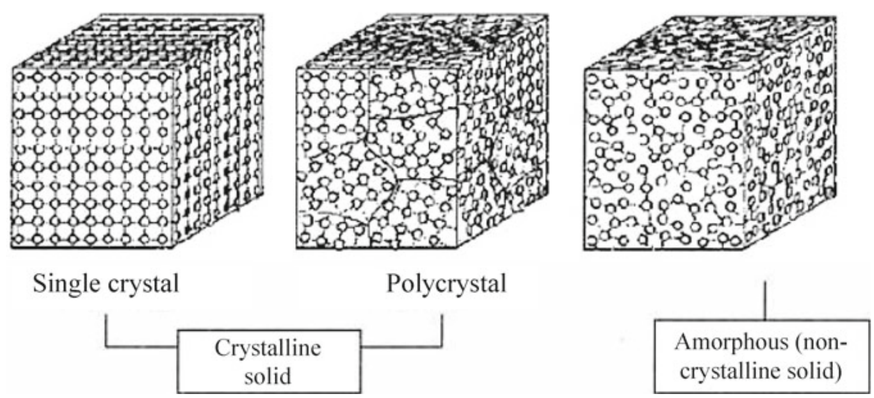

Fig. 2.2 Structure of ceramics (schematic)

This results when cleavage along atomic planes or crystal faces is possible because atomic bond strength is weak and density of bonds is low. It is well known that calcite tends to crack or cleave in three directions and that the fractured faces are flat planes. Mica also has pronounced cleavage and cracks into sheets.

Polycrystals are usually manufactured by sintering the materials in high-temperature furnaces. Polycrystals manufactured using this method are called "sintered bodies." Pottery and porcelain products are examples. Even if one type of compound is used as the raw material, boundaries with irregular structures are created between grains (grain boundaries). Therefore, sintered bodies exhibit properties not observed in single crystals. The grains are oriented in various directions, and in general, the directions do not determine the properties. Fractured surfaces of polycrystals are jagged and exhibit granular or semi-dull luster.

2.1.3 Amorphous: Glass and Other Amorphous Solids

"Amorphous" materials can also be divided into two types: (1) glass and (2) solids other than glass. Glass is normally made by melting glass material containing silicate at high temperatures and quenching it. It becomes a liquid with high viscosity below its solidification temperature. Hence, crystals are not formed (supercooled condition), and the viscosity increases as the temperature decreases. The material becomes a glass near the glass transition temperature, after which the free movement of atoms is no longer possible. The glass at this stage is considered to be a "rigid liquid." It is essentially in a thermodynamically unstable state and energetically favors crystallization at room temperature. We can use glass without worry because the time before it actually crystallizes is extremely long. In other words, materials that exhibit a "glass transition state" are glasses. Amorphous solids other than glasses are the same as glasses with respect to the homogeneous atomic arrangement without periodicity or regularity in a wide range. However, they are manufactured without the process of super-cooling or passing through the glass transition.

As for the cleavage of crystals, glass is homogeneous and the structure is non-directional (expressed as "isotropic"). Therefore, it fractures into various jagged shapes or shells, not flat objects (Note 2.2). Because glass is isotropic, it exhibits no difference with regards to the transmission of light in each direction in terms of optical properties.

Note 2.2 Some of the crystal solids such as garnet fracture into jagged shapes.

2.2 Composite Materials

2.2.1 Definition of Composite Materials

Composite materials, unlike monolithic ceramics explained in the previous section, are made by blending or combining multiple chemical compounds, metals and polymers. Each of the substances that constitute composite materials is often expressed as a "phase." Composite materials contain one or more phases that can be clearly distinguished from the matrix. The matrix is mixed with a variety of metals and polymers as well as ceramics. Earthenwares, potteries and porcelains, and mud walls that have been used in Japanese houses since early times are in a broad sense composite materials. Composite materials are also observed in a number of living organisms such as wood (composite of cellulose and lignin) and shells (composite of calcium carbonate and protein) as well as artifacts. Many of the composite materials created in nature have rational structures and high performance. Efforts are being made to utilize them in the designing and development of artificial materials.

Composite materials in a narrow sense are advanced materials made by combining multiple industrially-produced high-purity raw materials. Composite materials are represented by ferroconcrete, but advanced composite materials such as cutting tools, carbon fiber-reinforced carbon (C/C composite), fiber-reinforced plastic (FRP) have also been commercialized.

2.2.2 Structural Characteristics

Functions of composite materials can be controlled by adjusting the configuration and arrangement of dispersed phases. The dispersed phases include continuous fibers, short fibers, needle-like crystals (whiskers), platelet crystals and grains. In order to achieve the desired or high performance properties, these phases need to be homogeneously dispersed. Continuous fibers and whiskers featuring shape anisotropy are sometimes dispersed two- or three-dimensionally by facing them toward one direction or arranging them like a fabric. Fiber-reinforced ceramic composite materials, in which the expansion and growth of cracks within matrix material is blocked by continuous fibers (reinforcing materials), have extremely high toughness and high reliability in terms of dynamics.

Meanwhile, with respect to nanocomposite materials, in which the composite structure is controlled at the nanometer level, research on physical property characterization started in the 1980s, when ultrafine metal particles, etc. were added to the inorganic matrixes of ceramics, etc. Later, mechanical properties of structural ceramics were improved, which led to the development of materials with new properties and functions such as superplasticity and machinability. Ceramic nanocomposite materials are produced by dispersing nano-sized ceramic or metal particles as the second phase in the matrix of single crystal grains and by intentionally causing structural defects (stacking faults, dislocation, etc.) in order to improve the properties. The materials can also be used to enforce grain boundaries. They are classified into intragranular-type, intergranular-type, intra/intergranular-type, nano/nano-type, etc., as shown in Fig. 2.3.

In addition to particle dispersed composite materials explained as an example, nanocomposite materials made by utilizing nano-level grain-boundary phases as well as those made by adding carbon nanotubes, have been studied. Typical structural ceramics such as alumina and silicon nitride as well as dielectric materials and magnetic materials are used as the matrix of nanocomposite materials.

2.2.3 Functional Characteristics

The improvement of characteristics and the appearance of new functions through compositing are important and essential for composite materials. One of the aims of using composite

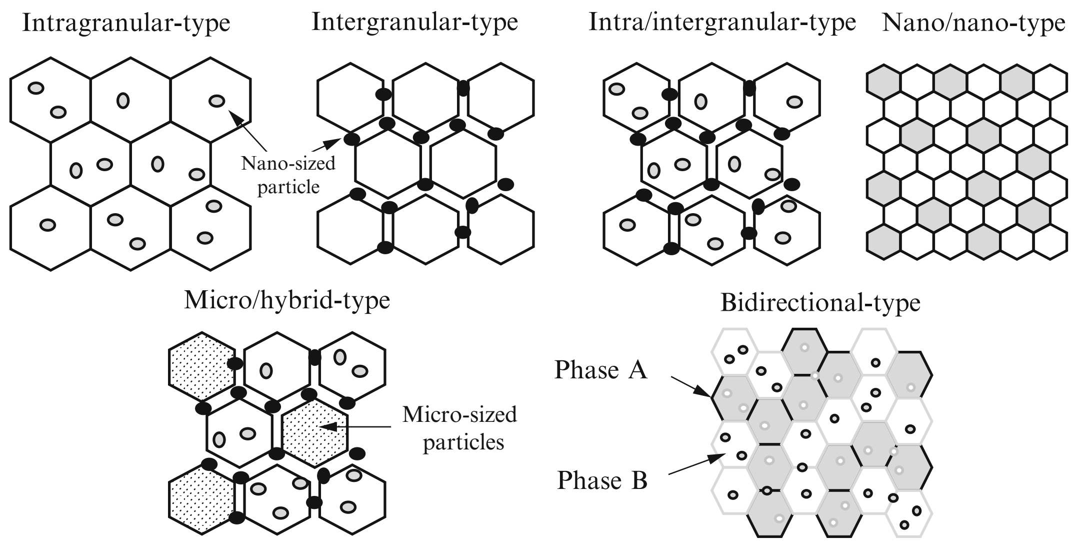

Fig. 2.3 Classification of nanocomposite materials by microstructure

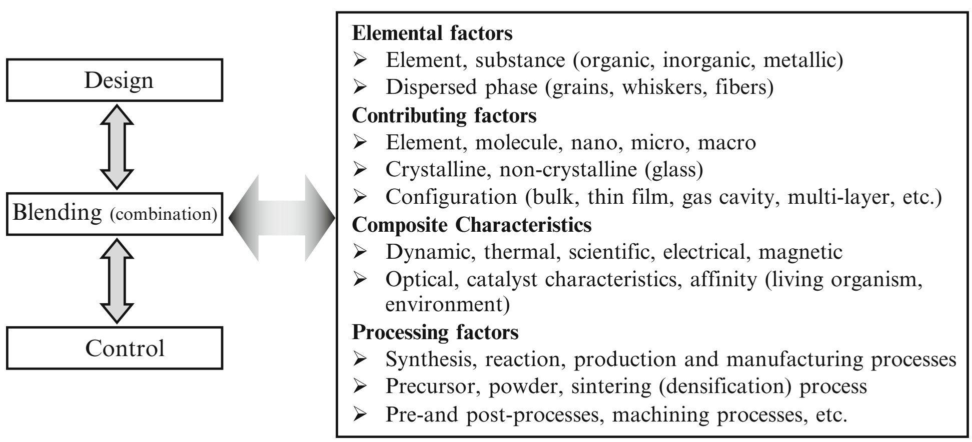

Fig. 2.4 Design guide for function-conscious ceramic matrix composite materials

materials is to improve the mechanical properties of the matrix. For example, the materials made by dispersing silicon carbide (SiC) in alumina (Al_2O_3) feature higher hardness, toughness and abrasion resistance than alumina and are used as cutting tools.

Meanwhile, composite materials with a focus on properties other than mechanical properties have also been developed. For example, ceramic composites that can be processed by electrical discharge have been developed by adding a certain amount of conductive substances such as nitride or carbide to ceramic materials, which are generally insulators (electrical discharge machining allows for the cutting into intended shapes). Electronic ceramics such as varistors and laminated capacitors also belong to composite materials in terms of their structures and functions.

2.2.4 Future Composite Materials and Their Issues

Materials that have multiple superior functionalities will be produced by the introduction of composites of various structural scales into ceramics. In order to realize materials of this kind, in addition to the combination of constituting factors such as types and configurations of materials (substances), what is needed is the design and control of multiple factors such as structural factors that include sizes and configurations, characteristic factors including mechanical and electromagnetic properties and processing factors involving material production, as shown in Fig. 2.4. For the creation of composite materials, advanced knowledge and understanding of technologies involving physics, chemistry and biochemistry will be required, in addition to conventional science and technologies relating to ceramic materials. Meanwhile, it is important to give due consideration to the environment and recyclability of micro- and nano-level composite materials.

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