Innovative Ceramics
In recent years, the development of new devices supporting advanced industries such as the semiconductor/IT industries, environmental industries, nuclear power, aerospace, and others, and development of equipment, higher efficiency, and reduction of environmental loads have been strongly required. The aims of the NIMS Nano Ceramics Center are to radically improve the fundamental properties of ceramic materials, such as optical and magnetic functions, heat resistance, and high strength, and to create multi-functional “innovative ceramics” by intentionally superimposing or refining those properties.

In addition to pursuing various nanoparticle processes and developing advanced versions of those processes, the Center is integrating all steps from the construction of guidelines for nanostructural design based on the mechanisms responsible for the manifestation of functions to the synthesis/evaluation of new functional materials, and is achieving new development through mutual collaboration.

The key element technologies for realizing this aim are (1) synthesis of nanoparticles with homogeneous composition and controlled crystal size, (2) nanoparticle arrangement with uniform particle size, integration, and dispersion control, and fabrication of ceramics with regular pore structures and utilization of that space, (3) high order structural control from the micrometer to the nanometer order, and (4) nanostructure design based on theoretical/experimental study of the relationship between local structures and the manifestation of object functions.

In particular, applying electrical, magnetic, electromagnetic, stress, and other types of external stimulation to the reaction field is effective for realizing advanced nanoparticle processes. In all cases, leading research on individual processes is carried out at NIMS, and as a result, NIMS boasts a high potential in all areas. Concrete element technologies include a technique for creation of nanoparticles using reactive thermal plasma, a technique for production of high purity non-oxide nanoparticles using precursors, a technique for production of high-performance non-oxide nanoparticles by a vapor phase process, advanced sintering techniques such as spark plasma sintering (SPS) and others (p. 6), a technique for textured development of ferro magnetic ceramics using a strong magnetic field (p. 4), film-forming by electrophoresis deposition (p. 8), a technique for fabrication of lamellar ceramics, and a technique for fabrication of regular porous ceramics by anodic oxidation (p. 9).

This Special Feature introduces recent achievements of the Nano Ceramics Center. We hope that the publication of these results will also lead to many collaborative projects and joint research.

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Today’s ceramics are becoming increasingly multi-functional materials, but the potential of ceramics as materials is still unknown. Applications are expanding into areas which would have been unimaginable only a few years ago, with the commercial application of SiAlON phosphors to LEDs at the top of the list. The Nano Ceramics Center takes full advantage of the outstanding process development and characterization technologies of NIMS as it continues to shine new light on ceramics.
Bio-inspired Machinable Nanolayered Ceramic: the Unprecedented Fracture Toughness and Strength

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Inspiration from nature.

It is rather difficult to believe that someone can produce ceramic materials with the bending strength of 1200 MPa, fracture toughness as high as 18 MPa m^{1/2}, and machinability comparable to that of steel.

In fact, to date, the strength and toughness of inorganic ceramics are very difficult to enhance simultaneously. Usually, these two factors show an opposite tendency. The intrinsic brittleness of ceramics also limits their wide application. The twin quests for reinforcement and ductility of ceramics have pushed many scientists to take inspiration from nature. Several millions years of natural selection and evolution permitted natural plants and animals to develop optimized microstructures to survive in severe environment conditions. The nacre shell microstructure consists of submicrometer scale layered grains with the plates aligned orderly. Thus, the microstructure configuration justifies its excellent tensile, compressive and shear behaviors. As in the case of the nacre shell, in order to simultaneously increase the fracture toughness and the bending stress, it is indispensable that the microstructure exhibits -weak grain boundary interfaces.-large and elongated grains.

Making nacre like microstructure.

Recently, nanosized artificial nacre was reproduced by sequential deposition of polyelectrolytes and clay. The bulk hybrid ceramic-based materials increased by four times the strength, while the fracture toughness was comparable to those of aluminum alloys. Unfortunately, the introduction of organic materials prohibits employment at high temperatures. MAX phases in which M is transition metal, A is a group element, X is C or N, and n is 1–3, because of their nanolayered structure, are ideal candidates to reproduce nacre’s microstructure. Among the MAX phases, Nb₄AlC₃ has been selected for investigation. As shown in Fig. 1, the weak bonding between Al atom layers with Nb and C atom layers contributes to the easy dislocation formation and their slipping which induce the development of kink bands in the grains presenting the ‘quasi-plastic’ behavior. Up to date, the strong magnetic field technique is the only available method to align nanolayered Nb₂AlC₃ particles. The strong magnetic field alignment technique permitted to obtain highly c-axis oriented Nb₂AlC₃ grains, while the high temperature annealing generated plate-like grains. The nacre shell-like microstructure with the layer stacking from nano-scale to milli-scale was obtained.

Increasing fracture toughness and strength.

Fig. 2a-c show the mechanical properties and toughening mechanisms of textured Nb₄AlC₃ ceramic. It is seen that the bending strength of samples is as high as 1184 ± 283.3 and 1219 ± 108.6 MPa when tested parallel and perpendicular to the c-axis (Fig. 2a). Also, as shown in Fig. 2b, the fracture toughness when tested parallel and perpendicular to c-axis are as high as 17.9 ± 5.16 and 11.49 ± 1.38 MPa m^{1/2} respectively. In comparison with those of untreated Nb₄AlC₃ ceramic, the bending strength and fracture toughness have been increased by factors of 3.5 and 2.5, respectively.

Undoubtedly, the microstructure design justifies the mechanical responses. The single edge notched bending (SENB) samples tested along the c-axis direction present the zigzag fracture mode. The zigzag fracture surface corresponds to high surface energy transformed from the mechanical energy. Additionally, the investigation of the microcracks zigzag fracture surface revealed pull-out grains distributed on the whole surface (Fig. 2c), which means that the toughening mechanisms possibly correspond to crack deflection which increases the surface energy and crack bridging which lowers the stress intensity factor at the crack tip.

Furthermore, the toughening mechanisms were evaluated by the precracking method. After testing, the sample still keeps the initial shape without complete fracture. The crack emanates from the notch and is prone to propagate along the symmetrical direction owing to the weak interfaces in the grains and at the grain boundaries in the textured ceramic. The crack branches can effectively absorb the mechanical energy for inhibiting the fast, catastrophic and straight crack propagation. The SEM micrograph in Fig. 3 clearly shows the toughening mechanisms due to crack deflection, grain pull-out and bridging. The plenty of weak interfaces promote the crack deflection. This result is ascribed to the orderly alignment of Nb₂AlC₃ plate-like grains.

Development of shell-like ceramics with high performance.

Fig. 4 shows the diagram of the flexural strength and fracture toughness of textured Nb₂AlC₃ ceramic in comparison with those of other advanced ceramics. It is observed that both the strength and toughness of textured Nb₂AlC₃ ceramics are the highest. It means that the present tailored ceramic possesses unprecedented mechanical properties. The strong magnetic field alignment technique successfully permitted the design of optimized microstructure with enhancement of both the strength and toughness. Undoubtedly, the as-prepared texture ceramic is a good candidate to be applied in the structural fields. Additionally, its applicability can be extended to high temperature fields. In fact, Nb₂AlC₃ ceramic retains ambient bending strength up to 1400°C without any degradation. In addition, it is extremely significant that the easy machinability of Nb₂AlC₃ is its intrinsic character for the shaping of complex structural parts.

Our fundamental investigation will guide the future development and design of shell-like ceramics with high performance.

References


Fig.1 Microstructure of textured Nb₄AlC₃ ceramic. Schematic map of layered nanolayered Nb₄AlC₃ ceramic, showing the orderly stacking of grains whose c-axes are perpendicular to the textured top surface (TTS).