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Smart Processing of 3D Micro Ceramic Devices by CAD/CAM Micro-Stereolithography and Sintering

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Abstract

Smart processing is a new concept of materials processing aiming to produce new material functions or improve performances through fine controlling and minimizing process energy and resources. We are developing various 3D micro ceramic devices by using CAD/CAM stereolithography and successive sintering as smart processing. Design and processing of micro gears and photonic crystals made of dense ZrO2 toughened Al2O3 (ZTA) and Al2O3 toughened SiO2 composites are demonstrated as well as their final mechanical and electromagnetic properties.

KEY WORDS: (Smart Processing) (Micro-Stereolithography) (Ceramic Gear), (Photonic Crystal) (ZTA)

1. Introduction

Smart processing which we proposed as a new development and manufacturing system of materials and devices in which the design, fabrication and evaluation are cycled to be optimized by employing computer aided design, manufacturing, evaluation system as represented in **Fig.1**. [1)]

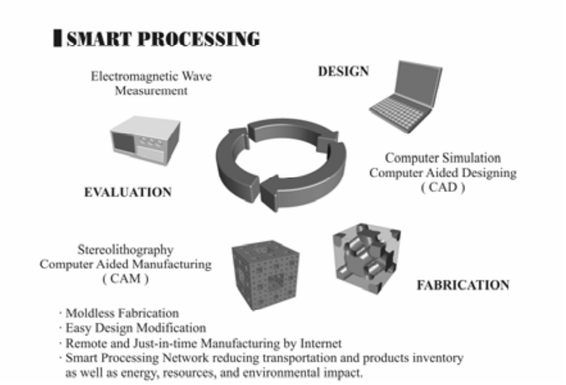

Fig.1 A schematic for the concept of smart processing.

We have combined a CAD/CAM stereolithography and a sintering process in order to develop various ceramic structures and devices.[2)] In smart processing, it is possible to fabricate, automatically and rapidly, 3D complex structures without molds. Custom-production or modification of structure is easy. By connecting the smart processing with the internet, remote and just-in-time manufacturing can be realized as well.

We report on smart processing development for various micro ceramic devices or structures and their functions demonstrated in micro gears and photonic crystals. Micro photonic crystals can control terahertz waves. Development of terahertz wave applications is an emergent issue for bio imaging and risk management such as the remote detection of gunpowder, drugs, counterfeit IC cards besides advanced communication, physical and chemical characterizations.[3)]

2. Micro-Stereolithography and Sintering Process

Stereolithography is known as a rapid prototyping for free-forming of resin and resin composites.[4)] CAD data of structure design is sliced into two dimensional figures on a computer and compiled into a set of STL files, then transferred to a stereolithogaphic machine. An ultraviolet laser beam scans the surface of photo curable liquid resin using a galvanic mirror and a two dimensional figure is solidified by photo polymerization. By repeating this laser irradiation and polymerization layer by layer, a three dimensional solid object is formed.

Recently, we have developed a new micro-stereolithographic machine (Acculas SI-C1000, D-MEC Co.Ltd., Tokyo, Japan) under collaboration with companies. It is the first commercial machine to prepare free-forming micro or meso scale structures.[5,6)] **Figure 2** shows a schematic diagram of the micro-stereolithogrphic machine. A two dimensional figure is projected with laser illumination through an objective lens using a DMD (Digital Micromirror Device), so that the figure can be reduced to micrometer scales. A photo-curable resin paste is squeezed out from a dispenser by controlling air

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pressure and spread out on the previously formed structure as thin as 2 μ m at minimum by moving a metal blade.

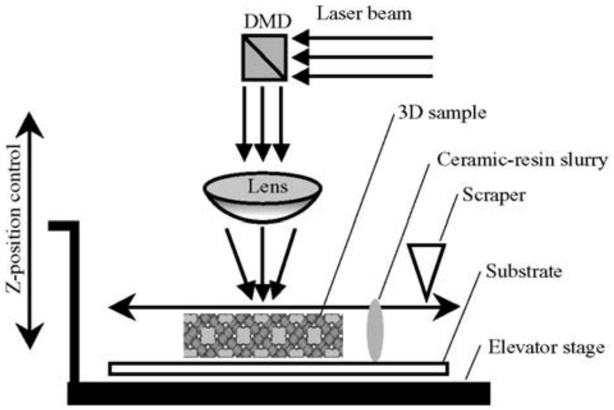

Fig.2 An illustration of micro-stereolithigrqaphy.

We incorporate various nanometer-sized ceramic powders at 40 to 50 vol.% into the photo- curable liquid resin to form objects of ceramics dispersed in resin. The dispersion of nanometer-sized ceramic particles imparts thixotropic flow to the ceramics/resin paste and reduces the dynamic viscosity when squeezing the surface layer. By dewaxing the ceramic/resin objects at an appropriate heating condition with a heating rate from 1 to 0.1 ˚C /min and keeping temperature at 600 ˚C, ceramic green bodies are obtained, and then sintered at a desired temperature.

3. Micro Fabrication of 3D Ceramic Devices

1) Micro Gears

Figure 3 shows a micro gear of zirconia toughened alumina (ZTA) sintered from an object of 40 vol.% ZTA particles (3Y-ZrO_2 with 1 μ m in average size, 20 wt%, Al_2O_3 with 170 nm) dispersed in acrylic resin (JL2129, D-MEC Co.Ltd, Tokyo, Japan) formed by micro-stereolithography. The sintering temperature was 1600 ˚C. The relative density and average shrinkage ratio were 96.5% and 26%, respectively. The micro Vickers hardness was 14 GPa. The indentation fracture toughness was 11 $MPam^{1/2}$. These excellent mechanical properties suggest a high potential for actual use of micro ZTA parts in MEMS, bio, and other applications.

2) Micro Photonic Crystals

Photonic crystals are periodic structures of dielectric or metal media which can totally reflect electromagnetic waves or light due to Bragg deflection and form photonic band gaps.[7] Research and development of photonic crystals has been intensively carried out in these last two decades for applications in various photonic or electromagnetic devices such as photonic circuits, filters, antennas, laser emissions, etc.

We are fabricating micro photonic crystals with diamond structures because these can open common band gaps in all directions. Such a complete photonic band gap is useful for various photonic and electromagnetic wave applications. **Figure 4** shows a ZTA photonic crystal with a diamond structure, which was sintered at 1600 ˚C from an object of 40 vol.% ZTA particles dispersed in acrylic resin. No deformation or cracking were observed. The relative density and the average shrinkage ratio were 97.5% and 25%, respectively. The unit cell size is 375 μ m. **Figure 5** shows a transmission spectrum of this sample along Γ-X<100> direction measured by means of terahertz wave spectroscopy (THz-TDS, J-Spec2001,

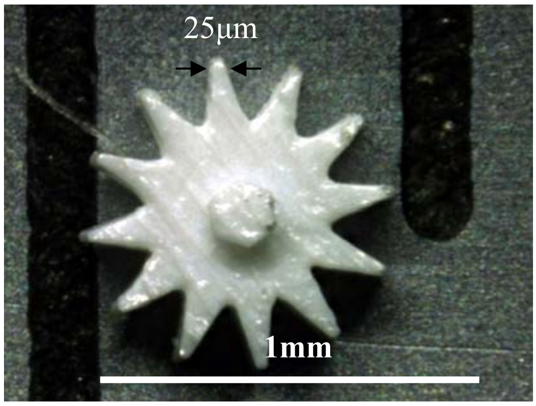

Fig.3 A micro gear of sintered ZTA.

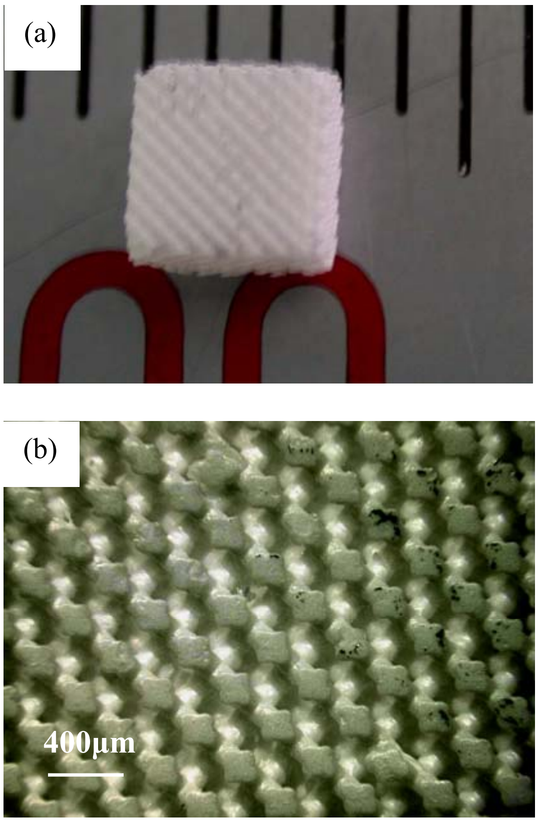

Fig.4 A micro photonic crystal of the sintered ZTA (a) with a diamond structure, and the top view at the (100) plane (b). The lattice constant is 375 μ m.

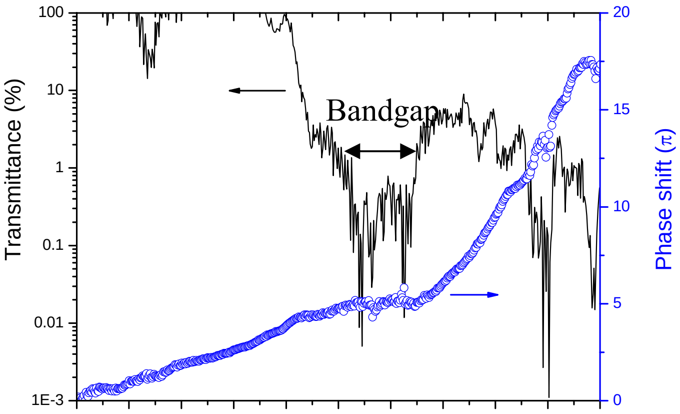

Fig.5 Transmission and phase shift spectra of terahertz waves for the sintered ZTA photonic crystal.

Advanced Infrared Spectroscopy Co.Ltd., Tokyo, Japan). The first band gap was observed clearly between 320-420 GHz. At the same range, the phase shift spectrum showed a jump. Theoretically, in the band gap frequencies, the propagation of an electromagnetic wave is inhibited by the formation of standing waves in the crystal.[7] These standing waves are caused by the interference between a traveling and reflected waves in a periodic lattice.

The transmittance of a sintered ZTA is 65% at around 400 GHz, while that of sintered SiO_2 is as high as 90%. The ceramics having high transmittance are required for applications in the terahertz range. However, the sintered SiO_2 is very weak and difficult to handle. Therefore, we tried to fabricate photonic crystals with Al_2O_3 toughened SiO_2 composite. **Figure 6** shows the sintered diamond structure of SiO_2-Al_2O_3 (10 vol.%) composite with a lattice constant of 440 μm. As

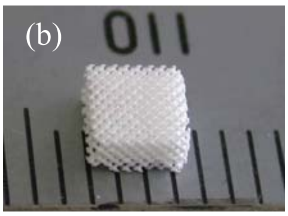

Fig.6 A micro photonic crystal of the sintered SiO_2-Al_2O_3 composite with a diamond structure. The lattice constant is 440 μm.

expected, this micro-scale 3D sample was strong enough for handling. A sintered photonic crystal was easily clamped without failure by steel tweezers.

Figure 7 shows the measured transmission intensity and phase shift spectra of the sintered 3D photonic crystal of SiO_2-Al_2O_3. The first and second band gaps were observed clearly between 470-540GHz and 750-820GHz, respectively, located in the THz range. It should be noted that in the band gap ranges, the phase shift spectra also showed a jump compared to that in other frequency ranges. The band diagram of a photonic crystal can be calculated from the structure parameters and dielectric constant of lattice materials by the plane wave expansion method.[8] The dielectric constant of the bulk SiO_2-Al_2O_3 composite made at the same condition was measured by THz-TDS, which was around 3.0 and the dielectric loss was below 0.1 in the range of 300-500 GHz. Thus, the band gap diagram for the current diamond structure was calculated. Considering the forming tolerance and sintering shrinkage, the aspect ratio of dielectric rod and lattice constant in the photonic crystals sintered was estimated to be 1.31 and 440 μm, respectively. As shown in **Fig. 8**, in the Γ-X <100> direction, the calculated first band gap was located in the range of 480-550GHz, which was consistent with the measured photonic band gap.

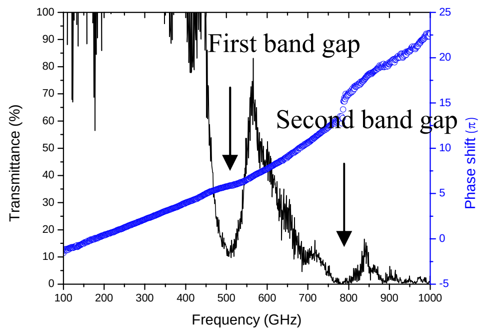

Fig.7 Transmission and phase shift spectra of terahertz waves for the sintered SiO_2-Al_2O_3 photonic crystal along the <100> direction.

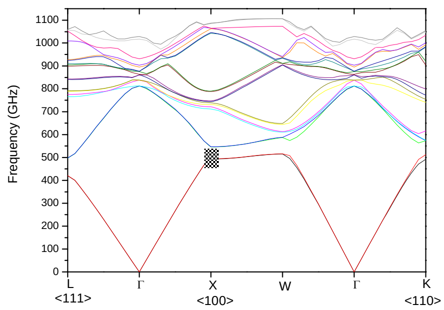

Fig.8 Calculated photonic band diagram for the SiO_2-Al_2O_3 photonic crystal by the plane wave expansion method. The shadowed area is the measured band gap.

4. Summary

Smart processing to develop 3D micro ceramic devices using newly developed micro-stereolithography and sintering has been demonstrated by fabricating a ZTA micro gear, ZTA and SiO_2-Al_2O_3 photonic crystals. The micro ZTA gear showed enough hardness and fracture toughness for applications in MEMS, micro ceramic actuators and micro electronic parts. Micro photonic crystals of dense ceramics demonstrated effective control of terahertz wave propagations. We expect that further development of smart processing will contribute to the 21st century's manufacturing system of ceramics.

Acknowledgments

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