Visualization of heat and stress flows in thermodynamic crystals fabricated by laser scanning stereolithography†

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1. Introduction

Thermodynamic crystals are new artificial materials with periodically percolated morphologies of metals and ceramics to control heat and stress flows intentionally by using laser scanning stereolithography, freeform sintering and precision casting. Artificial dislocations of point and plane defects were introduced to localize thermal and mechanical energies strongly through the computer aided design, manufacturing and evaluation. The alumina structures including air spheres with body centered cubic patterns were processed by using the stereolithography [1-4]. Resin slurries with pure copper particles were infiltrated into the formed ceramics objects. After heat treatments, the thermodynamic crystals with the metals spheres arrangements in the ceramics matrices could be obtained. These artificial microstructures were observed by using a digital optical and scanning electron microscope. Thermal and mechanical properties were simulated through a finite difference time domain simulation. The directional distributions of the heat and stress flows in the periodically percolated materials morphologies will be discussed.

2. Experimental Procedure

The three dimensional body center cubic structures were created by the computer aided graphical design application (Toyota Keram, Think Design) as shown in **Fig. 1**. The inverse crystal model of 10×10×10 mm in size included the air spheres of 4.0 mm in diameter. The lattice spacing for <100> direction was 4.5 mm. The volume ratio of the matrix was 26.5 %. The three dimensional ceramics models were fabricated automatically by using the stereolithographic machine (D-MEC, SI-C1000). The designed models were converted into the rapid prototyping format of the stereo-lithography files and sliced into thin sections. The alumina particles of 1.8 µm in average diameter were dispersed into the photo sensitive acrylic resin at 70 % in volume contents. The resin paste with the alumina particles was spread on a glass substrate with 50 µm in layer thickness by using a mechanically moved knife edge. An ultraviolet laser beam of 355 nm in wavelength and 100 µm in beam spot was scanned on the resin surface to create two dimensional images with 10 µm in scanning part accuracy. Through the layer by layer stacking processes, sub-millimeter order three dimensional composite models were formed successfully. After dewaxing process of alumina dispersed resin precursor at 600 ºC for 2 hs with heating rate of 1 ºC/min, the samples were sintered at 1500 ºC for 2hs with the heating rate of 8 ºC/min. Subsequently, the polyester resin past mixed with the pure copper particles of 75µm in diameter at 55 % in volume contents were percolated into the inverse ceramic structures. After the resin dewaxing for the infiltrated samples at 800 ºC for 2 hs with the heating rate of 1 ºC/min, the pure copper particles were sintered at 1000 ºC for 2hs with the heating rate of 8 ºC/min in an argon atmosphere. The relative densities of the sintered samples were measured by using Archimedes method. The part accuracy of the metal spheres arrangements in the ceramic matrices were measured by using a digital optical microscope (Keyence, VHX-200) system. And, the microstructures of the ceramic and metal phases were closely observed by using the scanning electron microscope (JEOL, JSM-6060). The heat and stress flows were simulated in the crystals by using a finite difference time domain application (Cybernet Systems, Ansys).

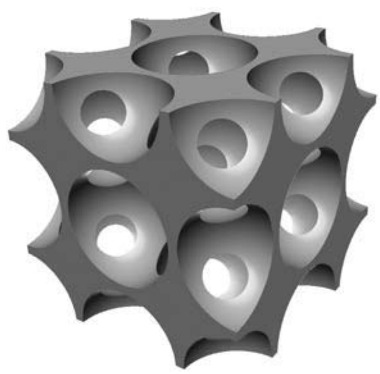

Fig. 1 A computer graphic model of thermodynamic crystal with an inverse body centered cubic lattice. Air spheres are closely arranged in a bulk to realize a spatial periodicity.

3. Results and Discussion

The three dimensional periodic structures composed of the alumina dispersed acrylic resin were processed exactly

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by using the stereolithography. The spatial resolution in the fabricated body was approximately 0.5 % in size. **Figure 2**(a) shows (100) planes of the sintered body centered cubic structure composed of the micrometer order alumina lattices including the air spheres. Deformation and cracking were not observed. Linear shrinkage on the horizontal axis was 6.5 % and that on the vertical axis was 7.8 %. It is possible to obtain the uniform shrinkage by designing an appropriate elongated structure in the vertical direction for compensating the gravity effect. The relative density reached at 98.5 %. Dense alumina microstructure was formed, and the average grain size was approximately 2 µm. Figure 2-(b) shows the (100) plane in the sintered thermodynamic crystal composed of the pure copper spheres and alumina matrix. Diffraction peaks indicating the formation of copper oxide phases did not appear in X-ray diffraction spectra. Sintering defects of cracks and pores were not observed in the microstructures of the copper phase. Smooth interfaces between the copper spheres and alumina matrices were obtained successfully. These material phases were joined continuously without intermediate layers. The heat and stress flow patterns in the fabricated thermodynamic crystals were simulated as shown in **Fig. 3**(a) and (b), respectively. The heat flow transmitted effectively from the source plane to the opposite side along the connected copper spheres of the percolated metal phases with high thermal conductivities. And, the tensile stresses were distributed periodically into the alumina lattices of the distributed ceramics phases with high Young's modulus. Through introductions of point or plane defects in to the perfect periodic structures, the heat and stress flows can be localized into the specific regions to control the thermal and mechanical properties of the artificial crystals.

4. Conclusions

Three dimensional thermodynamic crystals with body centered cubic structures composed of pure copper spheres arrangements in alumina matrices were fabricated by using stereolithography and heat treatment processes. The periodic arrangements with high part accuracies of dense

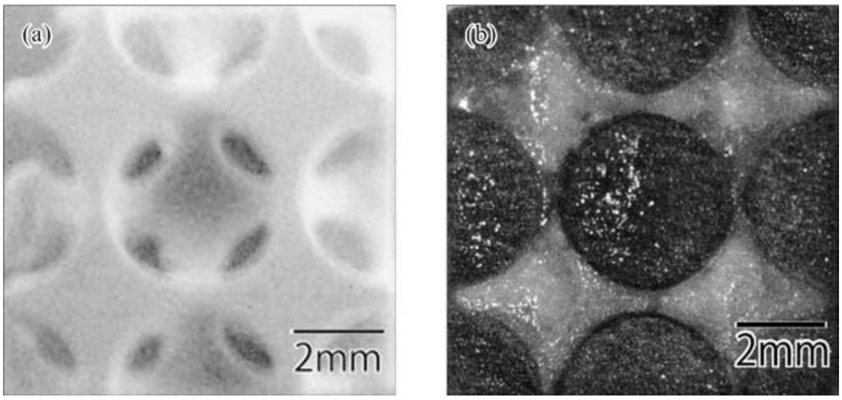

Fig. 2 A sintered alumina lattice with the inverse body centered cubic structure fabricated by using stereolithography of a structural joining process (a) and a formed thermodynamic crystal with periodic arrangements of pure copper spheres in an alumina matrix though powder sintering treatments (b).

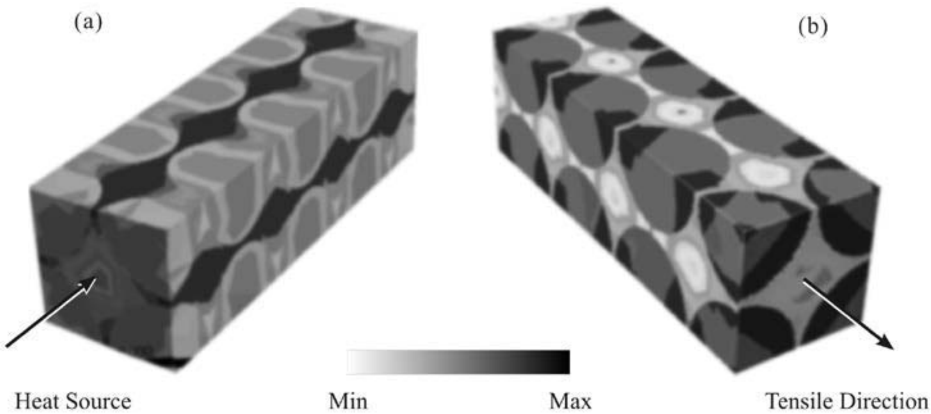

Fig. 3 The computer graphic models of simulated heat and stress distributions in the fabricated thermodynamic crystals with the body centered cubic structure. The graphics (a) and (b) show the heat and stress flows through the connected metal spheres and the continuous ceramic matrix, respectively.

alumina and copper phases were observed and verified by using a digital optical and scanning electron microscope. The heat and stress distributions in the thermodynamic crystals were simulated and discussed theoretically by finite difference time domain methods. The heat flow transmitted effectively through the connected copper spheres with high thermal conductivities, and the tensile stress were distributed in the alumina matrices periodically with high Young's modulus.

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