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1. Main Research Results

We aim to develop technology for increased reliability of ceramics, which will be key components for realizing secure systems. The main challenges are to provide basis for developing highly efficient superplastic forming of toughened ceramics. Furthermore, we are developing modeling and simulation technology to make more reliable ceramic components by controlling microstructural heterogeneity during sintering. The main research results are as follows;

1) Grain boundary network dynamics

Anisotroppic sintering stress for sintering of particles arranged in orthotropic symmetry

Many sintering bodies shrink in an anisotropic manner, when the particle packing is not isotropic. The thermodynamic driving force for the anisotropic shrinkage, that is the sintering stress tensor, is determined numerically for open pore structure with orthotropic symmetry in three dimensions. The sintering stress tensor is calculated rigorously by the energy method, the force balance method, and the volume averaging method. The deviatoric component of sintering stress is approximately proportional to the logarithm of the aspect ratio of the orthorhombic volume element, and it acts so as to deform the elongated particles to be more isotropic in most cases.

A microscopic model of interface-reaction-controlled sintering of spherical particles of different phases

A microscopic model is presented which describes the sintering of two-phase material where each phase may be crystalline. The formation and growth of interface between two phases are studied from a point of view of solid-state wetting. A wetting phase diagram of sintering is proposed to classify the equilibrium shapes in sintering of two spheres of different surface energies. The velocity of surface triple junction, or the contact line, is proportional to the force acting on it and the triple junction mobility. In sintering, as well as in grain growth, the deviation of dynamic contact angle from its equilibrium value is proportional to the contact line velocity and inversely proportional to the triple junction mobility. A micromechanical principle of shrinkage is also discussed with the use of sintering force and effective viscosity.

Local vs. global approach in the analysis of sintering kinetics

The sintering stress, which is the driving force of pore shrinkage in sintering, is evaluated by assessing the chemical potential difference in the system. For polycrystalline materials, a compressive normal traction, which is proportional to the grain boundary energy and inversely proportional to the grain size, arises from the force acting along grain boundary triple junctions. The sintering stress calculated by this local approach is the same with that obtained by the global approach.

Anisotropic viscosities and shrinkage rates in sintering

Macroscopic shrinkage in sintering is described as a linear function of sintering stress tensor [F Wakai, Y Shinoda. Acta Mater 2009;57:3955] and viscosity tensor, which is determined by taking into account the grain boundary diffusion mechanism and the anisotropy in microstructure. For a simple orthorhombic structure in equilibrium, the anisotropic shrinkage rate is dominated by the deviatoric component of viscosity tensor, which is approximately proportional to the logarithm of the aspect ratio of a volume element, and acts so as to deform the elongated structure to be more isotropic.

2) Superplasticity of nanocrystalline ceramics

Development of Creep-Resistant Tungsten Carbide Copper Cemented Carbide

Fine-grained tungsten carbide copper (WC-Cu) cemented carbide was sintered via spark plasma sintering at 1773K using a fine WC powder with a mean particle size of 0.11 mm. The mechanical properties were compared with tungsten carbide cobalt (WC-Co) cemented carbide and a binderless WC-sintered material. The Vickers hardness and fracture toughness obtained by the indentation fracture method for WC-10 mass% Cu cemented carbide were 1600 and 10 MPam0:5, respectively, which were in no way inferior to the values for WC-Co cemented carbide. Increasing the amount of copper improved the toughness and degraded the hardness. WC-Cu cemented carbide exhibited much higher creep resistance than WC-Co cemented carbide, and was the same as the binderless WC-sintered body up to 1273 K.

2. List of publications (original article, comment/book)

Original Paper

1) Anisotroppic sintering stress for sintering of particles arranged in orthotropic symmetry; F. Wakai and Y. Shinoda: *Acta Materialia*, **57**, 3955-3964 (2009).

2) A microscopic model of interface-reaction-controlled sintering of spherical particles of different phases; F. Wakai D. V. Louzguine-Luzgin and T. Kuroda: *J. Am. Ceram. Soc.*, **92**, 1663-1671 (2009).

3) High-temperature compressive deformation of SiAlON polycrystals prepared without additives; K. Chihara, D. Hiratsuka, J. Tatami, F. Wakai and K. Komeya: *Key Engineering Materials,* **403**, 117-120 (2009).

4) Development of creep-resistant tungsten carbide copper cemented carbide; Y. Shinoda, Y. Yanagisawa, T. Akatsu and F. Wakai: *Material Transactions*, **50**, 1250-1254 (2009).

5) Comment on "Local vs. global approach in the analysis of sintering kinetics"; F. Wakai and Y. Shinoda: *Scripta Materialia*, **62**, 117-119 (2010).

6) Anisotropic viscosities and shrinkage rates in sintering of particles arranged in a simple orthorhombic structure; F. Wakai and T. Akatsu: *Acta Materialia*, **58**, 1921-1927 (2010).

7) Micro-mechanical principle of sintering in particle-scale; F. Wakai: J. Jpn. Soc. Powder Powder Metallurgy, **56**, [10] 611-618 (2009).

Review & Books

1) Superplasticity; F. Wakai: pp.353-360 in Silicon Nitride-based Ceramics, Ed. JSPS 124 committee, Uchida Rokaku Ho, (2009).

3. Invited/Plenary Talks in Conference

International Conference or Workshop

1) F. Wakai; Grain boundary dynamics in nano/micro scale – Superplasticity, grain growth, and sintering: New Zealand – Tokyo Institute of Technology Seminar on

Nanotechnology, Tokyo Institute of Technology, 30 January, 2009.

2) F. Wakai, T. Akatsu, and Y. Shinoda; Constitutive model for superplastic sinter-forging – a reasonable application of ceramics superplasticity: International Conference on Superplasticity in Advanced Materials 2009 (ICSAM2009), Bell Harbor International Conference Center, Seattle, Washington June 29- July2, 2009.

Domestic Conferences

1) F. Wakai: Micro-mechanical principle of sintering in particle-scale; Jpn. Soc. Powder Powder Metallurgy, Kyoto, 3 June, 2009.

4. Patent

None

5. Others

1) J. Am Ceram Soc. Associate Editor

2) Science of Sintering, Associate Editor

3) Materials Science and Engineering A, Editorial member

4) Materials Transaction, Editorial member