APPLICATION OF HIGH MAGNETIC FIELD IN MATERIALS PROCESSING

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The history of Electromagnetic Processing of Materials (EPM) is described. The application of a high magnetic field in EPM is classified and then the two topics of quantitative evaluation of phase transformation and texture alignment of ceramics are introduced, which are our recent endeavors relating EPM to a high magnetic field.

1 Introduction

In the metal industry, electrical energy has long been used as heat energy due to its cleanliness, high controllability and high energy density. Technologies using electric energy were developed rather early and progressed without a background of sufficient scientific understanding. Good examples of this are electromagnetic levitation and electromagnetic mixing that were already invented in 1923 and 1932, respectively. To bridge the gap between technology and scientific understanding, magnetohydrodynamics which had been established by Alfven in 1942, was first introduced in 1982 at the IUTAM Conference titled "The Application of Magnetohydrodynamics to Metallurgy", held in Cambridge, England. The conference may have initiated many people into the field of Electromagnetic Processing of Materials (EPM), though the term "EPM" was first formally used at the initial Symposium of EPM held in Nagoya, Japan in 1994. EPM research has been hitherto devoted to the economics of mass production, and nanotechnology in relation to high quality materials. Today, EPM involves both Lorentz and magnetic forces relating to high magnetic fields.

Here, the application of a high magnetic field in EPM is classified and the two topics of quantitative evaluation of phase transformation and texture alignment of ceramics are introduced. These are our recent endeavors relating EPM to a high magnetic field.

2 Application of a High Magnetic Field in EPM

The technology relating to crystal orientation, structure alignment and spin chemistry has emerged in EPM thanks to the development of superconducting technology. Now, a high magnetic field utilizing a large space is now available even in small-scale laboratories. Table 1 indicates the utilization of a high magnetic field in EPM.

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A high magnetic field allows induction of crystal orientation, i.e. structural alignment, even in non-magnetic materials. There are four necessary conditions for crystal orientation under the imposition of a magnetic field. The first one is that unit crystal cells of the material have a magnetic anisotropy. The second is that the magnetization energy should be larger than thermal energy. The third is that materials should exist in the weak constraint medium in which a particle can rotate under a feeble magnetization force. The fourth is that each particle should be dispersed in the medium as a single crystal.

Table 1 Utilization of a high static magnetic field in EPM

Lorentz Force------Appearance of small electric current effect

Magnetization Force <	Mass TransportElimination of inclusions and surface defect $(\chi/\mu)(B \cdot \nabla)B$		
	Mass Rotation(Torque) MxB	Crystal orientation	vapor - deposition, electro - deposition magnetic slip casting organic molecular reaction phase transformation
		structual alignment	phase transformation

Spin Chemistry------Intermolecular cross-linking reaction

The possibility of magnetic transportation and magnetic rotation was examined under several processes, such as solidification [1-4], electro-deposition [5] vapor-deposition [6-8] and solid phase reaction [9]. The application of a high magnetic field has now been proved to be one of the promising methods used in EPM.

Strengthening of carbon fibers by imposition of a high magnetic field is an example of spin chemistry. Carbon fibers produced from PAN (polyacrylonitrile) as a precursor are generally subjected to the three heat treatment processes of stabilization and carbonization, followed by graphitization. The carbon fibers produced from stabilized fibers in a magnetic field showed higher tensile strength than those produced without a magnetic field [9]. The fibers processed in a magnetic field have a larger crystallite size than those treated in no magnetic field. An intermolecular cross-linking reaction model [10] describes the crystallite size increase due to the imposition of a high magnetic field. Regarding the spin chemistry [11-16] upon which the background of this model stems, one can say that this study is the first attempt to link EPM with spin chemistry. The development of materials processing based on the spin chemistry is considered to be a promising area in EPM.

3 Quantitative Evaluation of Phase Transformation

A new apparatus has been developed that can continuously measure the magnetic force during the phase transformation. The magnetic susceptibility is calculated from the magnetic force obtained by using the apparatus, then the transitional solid fraction during the solidifying and melting processes is evaluated from the magnetic susceptibility. The magnetic susceptibility was measured using the Gouy method [17,18] and is evaluated by measuring a magnetic force F_{z} .



Figure 1. Calculation of solid fraction.

$$\chi_{\rm m} = \frac{2L\mu_0}{m_{\rm s}(B_{\rm L}^2 - B_0^2)} F_{\rm z} \tag{1}$$

The solid fraction in a solid-liquid mixed phase can be calculated from the observed magnetic susceptibility, as follows. From Figure 1, which is a relationship between magnetic susceptibility and temperature, the magnetic susceptibilities of solid and liquid phases can both be expressed with good approximation by linear functions of the temperature around the melting point. Specifically, the magnetic susceptibilities in the single solid and liquid phases are given by Equations (2) and (3).

$$\chi_{\rm ml} = C_{11} T + C_{12} \tag{2}$$

$$\chi_{\rm ms} = C_{\rm s1} T + C_{\rm s2} \tag{3}$$

The magnetic susceptibility of a liquid and solid mixture is given by Equation (4).

$$\chi_{\rm m} = f_{\rm l} \chi_{\rm ml} + f_{\rm s} \chi_{\rm ms} \tag{4}$$

In addition, Equation (5) holds that

$$f_1 + f_s = 1$$
 (5)

Then

$$f_{s} = \frac{\chi_{m} - \chi_{ml}}{\chi_{ms} - \chi_{ml}}$$
(6)

Once the magnetic susceptibility χ_m and temperature of a mixture are measured, the solid fraction f_s can be derived from Eqns. (2), (3) and (6).

The relation between the solid fraction and temperature in the cooling process is shown in Figure 2. The solid phase of about 20mass% precipitated until the moment when the re-coalescence had finished and the temperature had recovered to the melting point. The liquid phase of about 20mass% remained even after the temperature descended below the melting point, i.e. about 20mass% of melt was supercooled.



Figure 2. The relation between temperature and solid fraction (cooling).

The method developed here can be applied to the direct observation of various phase transformation phenomena in solid, liquid and gas phases, therefore we hope it will lead to better understandings of various phase transformations and reactions.



Figure 3. Schematic view of the experimental apparatus used for rotating a crucible under a magnetic field.

4 A Novel Process to Fabricate Highly Textured Ceramics in a High Magnetic Field

A novel process, where a specimen is rotated during a slip casting under a high magnetic field, has been proposed in order to fabricate highly textured ceramics. The usefulness of the

newly proposed process has been confirmed in Si_3N_4 ceramics. Figure 3 shows the schematic of the experimental apparatus using rotation. In order to examine the effect of rotation, green samples were prepared in a magnetic field and without rotation. For comparison, a sample was also prepared with no magnetic field. After drying, the green samples were embedded in a 60wt%Si₃N₄ +40 wt% BN powder bed in a graphite crucible and heated to 1800°C for 1.5 hours in an N₂ atmosphere, with no magnetic field. Figure 4 schematically shows the functions of the magnetic field and the rotation. In the substance in which the magnetic susceptibility in the a, b axis is higher than that in the c-axis, $\chi_c < \chi_{a,b}$, a one-directional crystal orientation can not be obtained in a slip casting under a high magnetic field, as the free choice of crystal orientation exists in the a, b axis. When the magnetic field is imposed on the suspension, the c-axis of the particles can align perpendicular to the magnetic field. The condition where the specimen is rotated in the magnetic field is equivalent to the case where the specimen is fixed and the magnetic field is rotated. In this case, the c-axis of the particles will be perpendicular to the plane in which the magnetic field rotates. Thus, that the c-axis of the particles aligns parallel to the direction of gravity. Figure 5 shows the SEM micrograph of the polished surfaces of the specimen. Also, β - Si₃N₄ rod grains appear randomly distributed in the specimen prepared without exposure to a magnetic field (Figure 5. a and b). When the specimens are prepared by rotation under a magnetic field, a highly textured material can be obtained as shown in Figure 5(c) and (d).



Figure 4. Schematic view showing the functions of the magnetic field and rotation of a crucible in a magnetic field.

5 Conclusion

The history of Electromagnetic Processing of Materials (EPM) has been described. The application of a high magnetic field in EPM has been classified and listed and the two topics of quantitative evaluation of phase transformation and texture alignment of ceramics have been introduced, which are our recent endeavors relating EPM to a high magnetic field.



Figure 5. SEM micrographs of specimens made of α -Si₃N₄ powder with β -Si₃N₄ seeds: (a), (b) without magnetic field; (c), (d) with magnetic field under crucible rotation.

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References

- 1. H. Morikawa, K. Sassa and S. Asai: Mater. Trans., JIM, 39, (1998) pp. 814-818.
- 2. H. Yasuda, K. Tokieda and I. Ohnaka: *Mater. Trans.*, JIM, 41, (2000) pp. 1005-1021.
- 3. B.A. Legrand, D. Chateigner, R. Perrier de la Bathie and R. Tournier: *Journal of Magnetism and Magnetic Materials*, **173**, (1997) pp. 20-28.
- 4. J.G. Noudem, J. Beille, D. Bourgault, D. Chateigner and R. Tournier: *Physica C*, **264**, (1996) pp. 325-330.
- 5. T. Taniguchi, K. Sassa and S. Asai: *Mater. Trans., JIM*, 41, (2000) pp. 981-984.
- S. Mitani, H.L. Bai, Z.J. Wang, H. Fujimori and M. Motokawa: The 3rd International Symposium on Electromagnetic Processing of Materials, Japan, ISIJ, (2000) pp. 630-634.
- 7. M. Tahashi, K. Sassa, I. Hirabayashi and S. Asai: Mater. Trans., JIM, 41, (2000) pp. 985-990.
- 8. S. Awaji, K. Watanabe, Y. Ma and M. Motokawa: *Physica B*, **294-295**, (2001) pp. 482-485.
- 9. M. Ito, K. Sassa, M. Doyama, S. Yamada and S. Asai: TANSO, 191(2000), pp. 37-41.
- 10. M.G. Sung, K. Sassa, H. Ogawa, Y. Tanimoto and S. Asai: *Mater. Trans.* 43 (2001), pp. 2087-2091.
- 11. Y. Tanimoto, H.Hayashi, S. Nagakura, H. Sakuragi and K. Tokumaru: *Chem. Phys. Lett.* **41** (1976) p. 267.
- 12. N. Hatta, Chem. (1976) p.547.

- 13. K. Shulten, H. Staerk, A. Weller, H.J. Werner and B. Nickel: Z. Physik. Chem. NF 101(1976) p. 371.
- M.E. Michel-Beyerle, R. Haberkorn, W.Bube, E. Steffens, H. Schroder, H.J. Neusser, E.W. Schlag and H. Seidlitz: *Chem. Phys.* **17** (1976) p.139.
 I. Ihara, M. Kato, I. Kanamori, K. Nakamura, E. Shimada and T. Watanabe: Symposium on New
- I. Ihara, M. Kato, I. Kanamori, K. Nakamura, E. Shimada and T. Watanabe: Symposium on New Magneto-science 2002, Proceedings of the 6th Meeting, Nov. 2002, Tsukuba, Japan, pp. 298-302.
 S. Asai, K. Koumoto, Y. Matsushita, E. Yashima, M. Morinaga, K. Takeda, E. Iritani, T. Tagawa,
- S. Asai, K. Koumoto, Y. Matsushita, E. Yashima, M. Morinaga, K. Takeda, E. Iritani, T. Tagawa, M. Tanahashi, K. Miyazawa: *Science and Technology of Advanced Materials*, 4 (2003) to be published.
- 17. Y. Iguchi, Experimental chemical course 9, Maruzen Ltd. (1991) pp. 439-450.
- 18. N. Suzuki, Metal data book, Japan Metal Institute, Maruzen Ltd. (1974) pp. 10, 18.