Application of a strong magnetic field on materials fabrication and experimental simulation

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Abstract

A magnetic field has a lot of useful functions. We focus on two of these functions. The first one is alignment of crystals with magnetic anisotropy. We aligned hydroxyapatite crystals and graphite whiskers during slip casting process under the imposition of the high magnetic field. In the case of the hydroxyapatite crystals, the sample was rotated in the magnetic field. The second function we focus on is Lorentz force induced by an electrically conductive material motion submerged in the magnetic field. We experimentally simulated bubble motion in a liquid metal by using argon bubble in a sodium chloride solution.

Keywords: Hydroxyapatite; Carbon; Alignment; Bubble; Simulation

1. Introduction

A magnetic field has useful functions such as crystal alignment, levitation, separation, flow control of an electrically conductive fluid and so on. Thanks to the development of superconducting magnet technology, not only magnetic materials but also non-magnetic materials are affected by the magnetic field. The magnetic field is an attractive tool to produce a functional material because physical attributes of functional materials, such as their electric, magnetic, thermal and mechanical properties, are intensified by crystal alignment.

On the other hand, an electrically conductive fluid such as a liquid metal can be often controlled by using a magnetic field. Second phase motion in it is also affected through the reaction of the Lorentz force generated by interaction between the fluid motion and the magnetic field. Application of the magnetic field on materials fabrication is one of the promising ways in industry. However, only a few studies on the second phase motion have been reported until now.

In this paper, crystal alignment of hydroxyapatite and graphite, and new experimental simulation method of a bubble in a liquid metal submerged in the magnetic field are studied.

2. Alignment of hydroxyapatite

Hydroxyapatite (HAp), which is a main component of bones and teeth of vertebrates, is one of the bioactive ceramics. It has been widely applied as biomaterials such as a bone filler, an artificial dental root and a synthetic blood vessel. HAp is also a useful material for adsorbent in liquid chromatography because of its high-sorbability of proteins. Different kinds of functional groups in proteins are adsorbed on different planes of HAp crystals since HAp shows anisotropic adsorbing nature caused by its hexagonal crystal structure. For example, the c-plane of HAp is the adsorption site for amino acids in a protein and for sodium ions in a buffer solution, where phosphoric acid is mainly occupied in the crystal. On the other hand, the a,b-planes are the adsorption site for carboxyl groups in a protein, and for the phosphoric acid ion in a buffer solution, where calcium is mainly occupied in the crystal. This anisotropic nature is indispensable for the improvement of sorbability and bioactivity on a surface of biomaterials and adsorbents. The crystal alignment of HAp has been investigated by various methods such as slip casting under a static high-magnetic field [1], self-organized between HAp and collagen [2], hydrolysis reaction process [3] and pulse current pressure sintering [4]. These processes are complicated and it is not easy to obtain a bulk sample in which c-axis of HAp crystals aligned in the same direction by using some of these processes. On the other hand, it is reported that one-directional alignment of a polymeric material with magnetic susceptibility of \( x_c \leq x_{a,b} \) was successfully obtained using a rotating magnetic field [5].
To align the c-axis of hydroxyapatite crystals in the same direction, both a high-magnetic field and a mechanical rotation are applied in this study to a sample during a slip casting, and the resulting samples are examined by SEM and XRD.

2.1. Experimental procedure

The experimental apparatus is shown in Fig. 1. A slurry containing HAp particles (Taihei Chemical Co., Mean diameter: 2.17 μm) and distilled water was mixed with a deflocculant, and the mixed material was pounded in a mortar for 4 h to decompose aggregate particles into single crystals. The slurry was poured into a crucible with an inside diameter of 22 mm made of gypsum, and it was set in the bore of a superconducting magnet for a slip casting with a mold rotation or without rotation. To align the c-axis of each HAp crystal parallel to a gravitational direction in the slip casting process, the sample was rotated in horizontal plane under the imposition of the horizontal 10 T magnetic field. After the slip casting, the sample was dried in air over 24 h without a magnetic field and it was sintered at 1423 K in air in an electric furnace. For the quantitative evaluation of the crystal alignment on the upper surface of the sintered samples from the XRD patterns, an intensity ratio of (002) (corresponding to c-plane) to (211) (the main peak of the powder diffraction of HAp) was adopted as a crystal alignment index in this experiment. This index increases as the increase in crystals whose c-plane is parallel to the measured surface.

2.2. Results and discussion

The intensity ratios for the sample under the various experimental conditions are shown in Fig. 2. The index for the sample without magnetic field imposition and without mold rotation during the slip casting is 0.36, while that for the sample without magnetic field imposition and with mold rotation is 0.32. These results show that no obvious crystal alignment is observed for both the samples, and crystal alignment is not affected by the mold rotation for the sample without magnetic field imposition. For the sample with magnetic field imposition and without mold rotation, the intensity ratio becomes 0.71. This result shows that the c-plane on the upper surface of the sample somewhat increases by imposing only the high-magnetic field, but complete c-plane alignment of HAp crystals is not achieved. On the other hand, the intensity ratio for the sample formed with the high-magnetic field and with the mold rotation during the slip casting considerably increases to 53.0. That is, most of HAp crystals in this sample aligned with their c-plane perpendicular to the gravity direction by the mold rotation and the magnetic field imposition during the slip casting.

3. Alignment of graphite

Graphite has strong crystallographic anisotropy in thermal conductivity and electric conductivity. That is, its thermal conductivity in a,b-axis is 180 times larger than that in c-axis, and its electric conductivity in a,b-axis is about 1000 times larger than that in c-axis. Thus, crystal alignment of graphite is a promising method for the fabrication of a functional material.

The graphite whisker was produced by grinding the raw whisker powder using an automatic grinder. The slurry composed of the graphite whisker, the hide glue and distilled water, was agitated with a magnetic stirrer, and poured into a gypsum crucible. Then, the slip casting of the slurry was conducted under the magnetic fields of B=0 and 10 T to produce the green samples. After dehydration, the samples were dried in air. The crystal alignment of the green samples was evaluated by XRD measurement and SEM observation.

The XRD result of the graphite whisker samples is shown in Fig. 3(a). A lateral side and a cross-section of the graphite whisker are (002) and (004) corresponding to the c-plane were observed as shown in Fig. 3(a). On the contrary, for the case with the c-plane were detected as (002) and (110) corresponding to the a,b-plane were observed as shown in Fig. 3(b). The intensity ratio of (002)/(211) calculated from X-ray diffraction is shown in Fig. 2. The c-axis alignment has been promoted by the magnetic field with mold rotation.

![Fig. 1. Experimental apparatus.](image-url)  
![Fig. 2. Intensity ratio of (002) to (211) calculated from X-ray diffraction.](image-url)
Fig. 3. X-ray diffraction patterns of the samples obtained by slip casting in (a) $B=0$ T and (b) $B=10$ T.

Fig. 4. SEM photograph of samples obtained by slip casting in (a) $B=0$ T and (b) $B=10$ T.

solution produces Lorentz force, which affect the behavior of argon bubbles. This study gives new knowledge about the effect of Lorentz force on the bubble behavior.

4.1. Experimental set-up

A rectangular acrylic vessel was filled with saturated sodium chloride aqueous solution and was set in the bore of a super-conducting magnet generating a horizontal static magnetic flux density. An argon gas bubble was injected from the bottom of the vessel through a copper nozzle. The bubble motion was recorded by a high-speed camera to evaluate the bubble passing time of a certain distance in both the cases with and without the magnetic field. The effect of the magnetization force on the bubble motion is negligible in this experiment because the ratio of the magnetization force to the Lorentz force acting on the bubble is 0.05 in this experimental condition. The 3 mm bubble diameter in this experiment corresponds to the 2 mm diameter in the continuous casting process from the viewpoint of the similarity of the Froude number, and it corresponds to the 0.3 mm diameter from the viewpoint of the similarity of the ratio of the Lorentz force to the buoyancy force, and it corresponds to the 0.6 mm diameter from the viewpoint of the similarity of the Hartmann number, respectively.
4.2. Result

Fig. 5 shows the distribution of bubble velocity with and without the magnetic field. Under the imposition of the magnetic field on the sodium chloride aqueous solution, an averaged rising velocity of the bubbles is 0.207 m/s, while it is 0.229 m/s in the case without the magnetic field. Thus, it is concluded that the averaged rising velocity becomes slower by imposing a magnetic field. This might be the result that the liquid motion surrounding the bubble is suppressed by the Lorentz force.

5. Conclusion

C-axis aligned hydroxyapatite crystals are obtained using slip casting process with a simultaneous imposition of a high-magnetic field and a mold rotation.

Aligned graphite whiskers are obtained by applying a magnetic field during the slip casting process, in which the $a, b$-plane of the graphite whisker is parallel to the imposed magnetic field.

The rising velocity of an argon gas bubble in a saturated sodium chloride solution is suppressed by imposing a horizontal high-magnetic field.

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