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The control of crystal orientation in ceramics by imposition of a high magnetic field

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Abstract

From the viewpoint of high magnetic field effect, researches on which the crystal orientation of feeble magnetic ceramics was controlled by using a slip casting under a high magnetic field have been carefully reviewed. Both of the reported results and the experimental results obtained by the present authors indicate that gravity force also plays an important role for crystal alignment under a high magnetic field. In this study, by taking account of magnetic susceptibility, powder shape and magnetic field direction, a general rule of crystal alignment during slip casting under a high magnetic field has been derived.

Keywords: Control of crystal orientation; Slip casting; High magnetic field; Ceramics; Electromagnetic processing of materials

1. Introduction

The control of crystal orientation in ceramics is one effective way to improve their electrical, piezoelectric and mechanical properties [1,2]. Recently, a high magnetic field has been used to fabricate non-magnetic materials with textured structure where anisotropic magnetic energy should be strong enough to induce preferred crystal orientation. The magnetic force generated from a magnetic field can be classified into two kinds: an attractive or repulsive force, and a rotational force that makes a certain axis of a crystal parallel to the magnetic field direction. The former force has been used for magnetic separations [3], magnetic levitations [4] and measurements for magnetic susceptibilities of materials. The latter one has been applied on crystal alignment of materials that possess magnetic susceptibility difference due to crystal and shape magnetic anisotropies [5–14].

A large number of materials have the crystal magnetic anisotropy where the magnetic susceptibility is different in each crystal direction. However, making use of the magnetic susceptibility difference between axes has for long time been neglected since the difference is usually too small. This situation has changed owing to the development of super conducting technologies. Recently, some researchers [15–25] reported that crystals in feeble magnetic materials can be highly oriented by using a high magnetic field. In these researches, a conventional process of slip casting followed with sintering was used, during which a high magnetic field was imposed on suspension of powder.

In this paper, the reported results on crystal orientation of several ceramic materials under a high magnetic field are carefully examined. Based on the reported results and the experiments conducted by the present authors, a general rule of magnetic alignment of crystals with different magnetic susceptibility and different shape has been derived.

2. Experimental procedure and results

Preparation of a well dispersed suspension with individual single crystal particles is an essential condition for crystal alignment under a high magnetic field, because agglomerated particles in the suspension will prevent them from rotating. In the experiments mentioned in this paper, a colloidal processing, which enables dispersion of suspended particles by adding some kinds of deflocculant, was used. After the colloidal processing, the dispersed particles were slip-casted under a high magnetic field to make green samples, which were subsequently sintered in different temperatures. Fig. 1 is the schematic illus-

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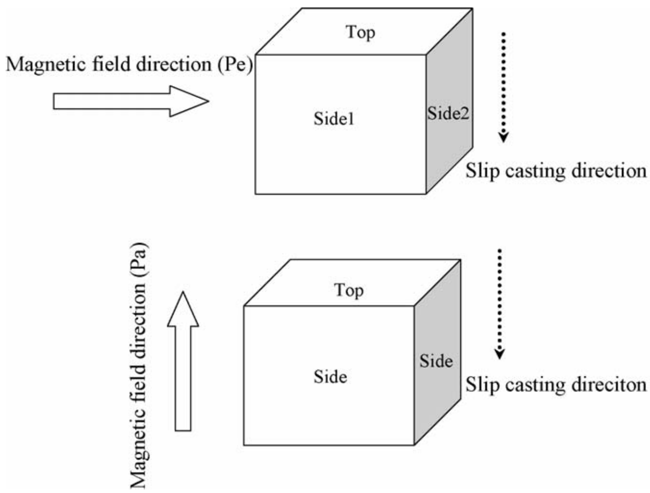

Fig. 1. A schematic view of the magnetic field direction and the definition of the specimen surfaces.

tration showing the direction of an imposed magnetic field with respect to each surface of a sample. When the direction of the magnetic field is parallel and perpendicular to the slip casting direction, we denote the magnetic field direction as Pa and Pe magnetic fields, respectively. The definition of the top, side 1 and side 2 surfaces of the sample are also shown in Fig. 1. When a Pa magnetic field is imposed, the side 1 and side 2 surfaces are defined as side surface since they are equivalent in this case.

By using a slip casting under a high magnetic field, researches on the texture control of TiO_2, Al_2O_3 and ZnO ceramics have been reported by Sakka et al. [15,16,19,24], while the present authors have also studied similar researches of hydroxyapatite (HAp) and Si_3N_4 [23,25] ceramics. These previously reported results were reviewed and listed in Table 1 with respect of the crystal structure, magnetic susceptibility difference and shape of particles.

When the Pa magnetic field is imposed on samples of TiO_2 and Al_2O_3 in spherical particles, XRD measurements indicated that the intensities of (0 0 l) peaks corresponding to c plane are relatively high in the top surface of the samples, while the intensities of ($h\,k\,0$) peaks corresponding to a, b plane are relatively high in the side surface of the samples. These results indicate that a preferred crystal oriented structure with c-axis parallel to the magnetic field direction has been obtained. While in the case of HAp and Si_3N_4 ceramics, which are also composed of spherical particles, it was found that a, b axis of the crystals prefer to align parallel to the magnetic field direction. Especially in the experiment of Si_3N_4 ceramics, SEM photographs indicated that a great deal of a, b planes appear on the top surface, while c plane and a, b plane coexist on the side surface.

In the experiment of ZnO ceramics, which has rod shape particles, the Pa magnetic field was applied on the suspension during a slip casting. It was found that the intensities of (1 0 0), (1 1 0) and (1 0 1) peaks were large in the top surface. By contrast, in the side surface, all of the peaks of (1 0 0), (0 0 2), (1 0 1), (1 0 2) and (1 0 3) showed relative large intensities. Therefore, it can be concluded that the a, b-axes of ZnO crystals were aligned parallel to the magnetic field direction.

In the experiment of TiO_2 ceramics fabricated from whiskers that had a rod shape, the Pa and Pe magnetic fields of 10 T were applied on the suspension during a slip casting. And the long-axis of TiO_2 crystal was confirmed to be c-axis based on its electron diffraction pattern. The features of X-ray diffraction patterns of the top and side were similar when the magnetic field was not applied. This means that the TiO_2 whiskers were randomly distributed in the case without magnetic field. A similar result was obtained in the case when a Pa magnetic field was imposed. However, when the Pe magnetic field was imposed, the X-ray diffraction pattern of side 2 was very different with the side 1 and top surfaces. In the top and side 1 surfaces, the intensity of (1 1 0) was large while those of (1 0 1) and (0 0 2) were small. However, in the side 2 surface, the intensity of (0 0 2) was very large. These results indicate that c-axis of the whisker was aligned in the magnetic field direction.

3. Discussion

A method [26] to evaluate the degree of crystalline texture from the intensity of X-ray diffraction pattern is applied here as given in Eq. (1).

$$\theta_F = \frac{\sum(I_{hkl} \times \theta_{hkl})}{\sum I_{hkl}}, \tag{1}$$

where θ_F is defined as the relative facial angle (RFA) measured from c plane, θ_{hkl} the facial angle between ($h\,k\,l$) and ($0\,0\,n$) planes, I_{hkl} the intensity of ($h\,k\,l$) plane obtained from the X-ray diffraction pattern. The RFA has the value of 0° or 90° when all crystals are aligned to c plane or a, b plane, respectively. According to the XRD profiles given out in previous researches, the RFA of the specimens in ceramics have been calculated. The difference of the RFA obtained from experiment and that calculated from JCPDS card is called a relative rotation angle (RRA). The RFA obtained from the experimental data and JCPDS card and the RRA are shown in Table 1. It can be seen from Table 1 that the crystal texture of the ceramics with the magnetic anisotropy crystal can be controlled by the slip casting under a high magnetic field, followed with sintering.

3.1. Theoretical consideration

When a non-magnetic substance is magnetized in a magnetic field, magnetization energy of substances is given by Eq. (2).

$$U = -\int_0^{B/\mu_0} M\,dB_{\text{in}}, \tag{2}$$

in which M is the magnetization, B and B_{in} the imposed magnetic flux density and the magnetic flux density in the substance, respectively, and μ_0 the permeability in vacuum ($4\pi \times 10^{-7}$(H/m)). The principle of crystal alignment using a magnetic field is that a torque rotates a crystal to take a stable crystal orientation so as to decrease the magnetization energy.