Proceedings

The 2nd Asian Workshop on Electromagnetic Processing of Materials

(Asian-EPM2005)

ASIAN - EPM 2005

May 23-25, 2005

Key Laboratory of EPM (Ministry of Education)

Northeastern University

Shenyang, China

Northeastern University Press

Proceedings

The 2nd Asian Workshop on Electromagnetic Processing of Materials

(Asian-EPM2005)

Editor-in-chief Ji-Cheng He

May 23-25, 2005

Key Laboratory of EPM (Ministry of Education)

Northeastern University

Shenyang, China

Supported by

K.C. WONG EDUCATION FOUNDATION, HONG KONG

NATIONAL NATURAL SCIENCE FOUNDATION OF CHINA

Northeastern University Press

Shenyang, China

图书在版编目（CIP）数据

第二届亚洲材料电磁过程学术研讨会论文集 / 赫冀成主编 .— 沈阳 ：东北大学出版社，2005.9
ISBN 7-81102-186-2

Ⅰ.第… Ⅱ.赫… Ⅲ.①材料电磁过程 ②学术研讨会论文集—亚洲 Ⅳ.Q4

中国版本图书馆 CIP 数据核字（2005）第 093423 号

出 版 者：东北大学出版社
地址：沈阳市和平区文化路 3 号巷 11 号
邮编：110004
电话：024—83687331（市场部） 83680267（社务室）
传真：024—83680180（市场部） 83680265（社务室）
E-mail：neuph @ neupress.com
http：//www.neupress.com
印 刷 者：沈阳市政二公司印刷厂
发 行 者：东北大学出版社
幅面尺寸：210mm×285mm
插　　页：2
印　　张：20.25
字　　数：768 千字
出版时间：2005 年 9 月第 1 版
印刷时间：2005 年 9 月第 1 次印刷
责任编辑：文　韬　　责任校对：米　戎
封面设计：唐敏智　　责任出版：杨华宁

定　　价：120.00 元

General Information

The 2nd Asian Workshop on Electromagnetic Processing of Materials (Asian - EPM2005) was held in the Meeting Hall of the Key Laboratory of EPM (Ministry of Education). Northeastern University, Shenyang, China, during 23rd to 25th May, 2005.

In 2004, the 1st Asian Workshop on EPM was held in Tokyo, Japan, promoted mainly by the scientists from Japan, Korea and China. The success of this workshop made a great contribution to EPM, the internationally booming research field. Asian - EPM2005 will provide scientists and scholars in this area a forum on all aspects of EPM, foster the exchange of ideas, techniques, experiments and enhance the international collaborations.

This workshop will be sponsored by the Branch Committee of Electromagnetic Metallurgy & Materials Science with High Magnetic Fields (the Chinese Society for Metals), the Division of Materials, Science & Technology Committee (Ministry of Education, China) and Northeastern University (China) and financially supported by " K. C. WONG Education Foundation, Hong Kong" and " National Natural Science Foundation of China".

Scope of the Workshop

Asian - EPM2005 will focus on the latest developments in

(1) Fundamentals
(2) Magnetohydrodynamics and numerical simulation
(3) EPM flow control and stirring
(4) EPM and solidification microstructure
(5) EPM applied to continuous casting
(6) High magnetic filed applied to materials processing
(7) Induction heating and melting
(8) Measurement and equipment

The contributions are expected to be oriented but not limited to the recent results in EPM.

Organization Committee

Chairman	**Ji-Cheng He**	*Northeastern University, China*
Co-Chairmen	**Liahg Zuo**	*Northeastern University, China*
	Jian-Zhong Cui	*Northeastern University, China*
Secretary-General	**En-Gang Wang**	*Northeastern University, China*
Members:		
	Fu-Xiao Yu	*Northeastern University, China*
	Jian Cui	*Baoshan Iron & Steel Co., LTD, China*
	Jing-Jie Guo	*Harbin Institute of Technology, China*
	Lin Liu	*Northwestern Polytechnology University, China*
	Ting-Ju Li	*Dalian University of Technology, China*

Wei Liu	*Tsinghua University, China*
Yuan-Sheng Yang	*Institute of Metal Research, CAS, China*
Zhong-Ming Ren	*Shanghai University, China*

International Advisory Committee

Gunter Gerbeth	*Forschungszentrum Rossendorf, Germany*
Heng-Zhi Fu	*Northwestern Polytechnology University, China*
Ho-Young Kim	*POSCO, Korea*
Joon Pyo Park	*Research Institute of Industrial Science & Technology, Korea*
S. Ranganathan	*Indian Institute of Science, India*
Shigeo Asai	*Nagoya University, Japan*
Shoji Taniguchi	*Tohoku University, Japan*
Takehiko Toh	*Nippon Steel Corporation, Japan*
Tie-Yong Zuo	*Beijing University of Technology, China*
Yasuo Kishimoto	*JFE Steel Corporation, Japan*
Yves Fautrelle	*Institut National Polytechnique de Grenoble, France*
Zhuang-Qi Hu	*Institute of Metal Research, CAS, China*

Contact Address

Professor En-Gang WANG

Key Laboratory of EPM (Ministry of Education), Northeastern University
Add: P. O. Box 314, Northeastern University
No. 3-11, Wenhua Road, Heping District, Shenyang, 110004, China
Tel: +86-24-83681739, 83681758
Fax: +86-24-83681758
Email: egwang@ mail. neu. edu. cn

Contents

Section 1 Invited Lecture

Section 2 Continuous Casting

Section 3 Solidification & Texture

Section 4 High Magnetic Field

Section 5 Fundamentals

Section 1

Invited Lecture

Recent EPM Activities in Nagoya University

Shigeo Asai
Nagoya University, Furo-cho, Chikusa, Nagoya, 464-8603, Japan

Abstract: EPM activities in Nagoya University in the last two years are classified in the application of Lorentz force and Magnetization force. The former is (1) development of a magnetic valve and (2) visual simulation of bubble behavior in a molten metal under a magnetic field. (3) in situ measurement of phase transformation, (4) crystal orientation of ceramics in a slip casting and sintering processes, and (5) composite crystal orientation in HAp and collargen are belong to the latter. Here (1), (3) and (4) are briefly described together with future prospect.

1. Introduction

In the last 2 years we have mainly involved into EPM relating to a high magnetic field. This activity has started 1990s by introducing a helium free super-conducting magnet, which was the second one in this type magnets produced by a Japanese company and now they say about 250 magnets in the type are running through Japan, mainly in academic field. At first we were excited by facing various new phenomena observed under a high magnetic field. Then our interest was led to functions which can be introduced only by use of a high magnetic field, such as crystal orientation and enhancement of a small current based on magnetization force and Lorentz force, respectively. Now most of phenomena accompanied by a high magnetic field, except a few examples, are able to be classified into the known functions and people pay more attention to the industrial application of a high magnetic field. In this paper the recent activities of EPM in Nagoya University are introduced. And the future prospect is discussed.

2. Application of high magnetic field in EPM

2.1 Classification of functions accompanied by high magnetic field

Owing to the development of super conducting technologies, by which a high magnetic field with rather large space is now available even in conventional scale laboratories, the technology relating to crystal orientation, structure alignment and spin chemistry has first been introduced in EPM. Table 1 indicates the classification of functions accompanied by a high magnetic field in EPM. The high magnetic field enables not only to enhance the various functions based on Lorentz force but also to induce several functions based on the magnetization force. The crystal orientation and the structure alignment in non-magnetic materials are typical examples introduced by use of the magnetization force. Four necessary conditions have to be satisfied for the crystal orientation under the imposition of a magnetic field. Firstly

Tel. 81-52-789-4646, Fax. 81-52-789-3247, e-mail: asai@numse.nagoya-u.ac.jp

a unit crystal cell of materials to be oriented should have a magnetic anisotropy. The second is that the magnetization energy provided by magnetic field should be larger than thermal energy to lead to thermal perturbation. The third condition is that the materials should exist in the weak constraint medium in which a particle composed by the materials can rotate by such a feeble magnetization force. The fourth is that each particle composed by a single crystal should be dispersed in the medium.

Table 1 Utilization of a high static magnetic field in EPM

- Lorentz Force
  - *Strong brake effect in liquid metal flow*
  - Enhancement of Lorentz force in small electric current
- Magnetization Force
  - Mass Transport——Elimination 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
    - Structural alignment phase transformation
- Magnetization energy——Crystal orientation accompanied by crystal growth
- Spin Chemistry——Intermolecular cross-linking reaction

The possibility of mass transport and mass rotation due to the magnetization force was studied under several processes such as solidification[1-4], electro-deposition[5] vapor-deposition[6-8] and solid phase reaction[9]. Now people have recognized the application of a high magnetic field is surely useful and promising methods in EPM.

2.2 Magnetic valve of molten metal flow

A static magnetic field has a function to suppress a molten metal flow, which has already been applied on a single crystal production of silicon industry as a magnetic Czochralski method and a steel production as a magnetic brake in a continuous casting process. In these cases, the magnetic flux density is 0.5 T at mo st.

A molten metal flow in a duct channel under a magnetic field is called a Hartmann problem, where the braking effect is drastically increased by increasing a field intensity up to 5～10 T. In order to demonstrate the braking effect, the mean metal flows from a tank with metal height of 60mm were observed in a model experimental apparatus shown in Fig. 1. At 5 T, a channel metal flow was declined to about 7/1000 of the flow without magnetic field. This result suggests that the function of suppressing of a metal flow is useful and will be used in a metals industry in the near future accompanying with the further development of superconducting technologies.

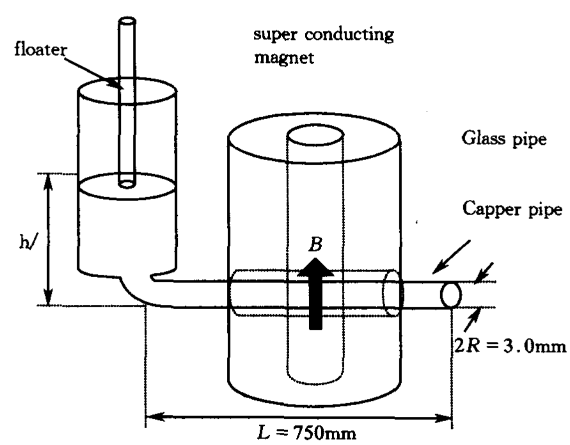

Fig.1 Experimental apparatus

Furthermore, a magnetic dam is available by simultaneous imposition of a high magnetic field and an electric current. This is also a promising technology in metal processes such as galvanization, ejecting of molten metal from a cold crucible and a side dam of a twin roll casting. Fig. 2 demonstrates that a stable holding of a molten metal is available under the conditions between the simultaneous imposition of 4 T and 0.91 A and 4T and 1.5A. Under the condition of 4T and 0.7A the front of a molten metal coming from a right hand side of an upwind side was almost held between electrodes but not be completed. That is, it passed through the portion of the electrodes after 15 seconds. The other hand under the condition of 4T and 1.74A the front was deeply depressed toward the upwind side, and at 4T and 2.1A an unstable switching behavior which repeats touching and detaching electrodes was observed.

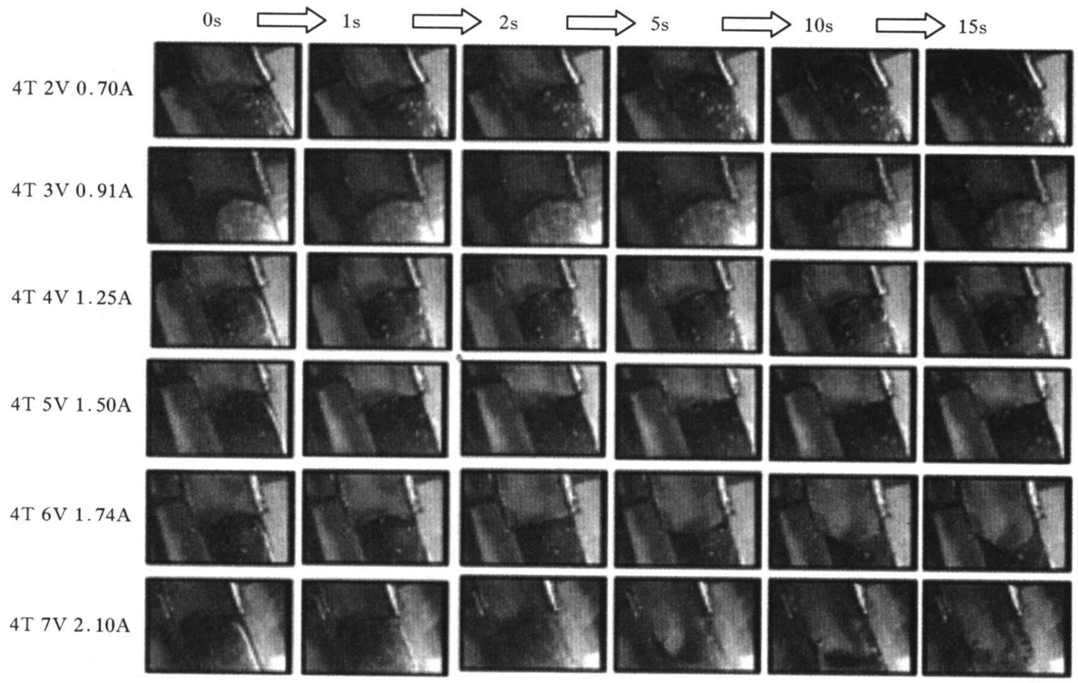

Fig. 2 A molten metal behavior between electrodes

3. Qualitative evaluation of phase transformation

3.1 Principle

A magnetic susceptibility of a mixture with two components is given by Eq (1).

$$\chi_m = f_1\chi_1 + f_2\chi_2 \quad (1)$$

where f_1 and f_2 are a fraction of the two components, respectively. In addition, Eq. (2) holds obviously.

$$f_1 + f_2 = 1 \quad (2)$$

Once the magnetic susceptibility χ_m is measured, the fractions of each component in the mixture can be derived from Eqs. (1) and (2).

$$f_l = \frac{\chi_m - \chi_2}{\chi_1 - \chi_2},\ f_2 = \frac{\chi_m - \chi_1}{\chi_2 - \chi_1} \quad (3)$$

Here, the magnetic susceptibility can be obtained by the use of Gouy method[10, 11] which is based on the measurement of a magnetization force F_z. as Eq. (4).

$$\chi_m = \frac{2L\mu_0}{m_s(B_L^2 - B_0^2)}F_z \tag{4}$$

where L and m_s are a length and a mass of the specimen, respectively. μ_0 is a magnetic permeability and B_L and B_0 are magnetic flux densities at the top and bottom of the specimen, respectively. And the magnetization force F_z can be obtained from the difference between the weights of a specimen measured under the imposition with and without magnetic field.

When we apply the principle to evaluate a phase fraction change during a phase transformation, we have to measure a temperature of the specimen together with the magnetization force since the magnetic susceptibility is a function of temperature to evaluate the values of χ_1 and χ_2. appearing in Eq. (3) beforehand.

3.2 Measuring solid fraction during solidification

We can figure the relationship between the magnetic susceptibility and temperature measured during the solidification of an alloy as shown in Fig. 3. It is found that the magnetic susceptibilities of solid and liquid phases can both be expressed as a linear function of the temperature around the melting point with a good approximation. That is, the magnetic susceptibilities in the single solid and liquid phases are given by Eqs. (5) and (6).

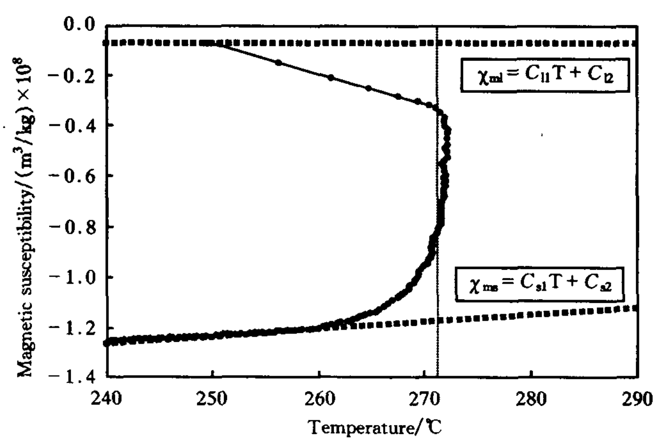

Fig. 3 Calculation of solid fraction

$$\chi_{ml} = C_{l1}T + C_{l2} \tag{5}$$

$$\chi_{ms} = C_{s1}T + C_{s2} \tag{6}$$

By substituting χ_{ml} and χ_{ms} evaluated from Eqs. (5) and (6) into Eq. (3), the relation between the solid fraction and temperature during solidifying of Zinc is obtained as Fig. 4. It is noticed that the solid phase of about 50mass% has precipitated at the moment when the recalescence finishes and the temperature comes back to the melting point.

3.3 Phase transformation from γ phase to α phase in carbon steel

Let us consider the phase transformation from γ to α in carbon steel taken place above the Curie point, where γ and α phases are paramagnetic. Eqs. (1), (2) and (3) are expressed as Eqs. (7), (8) and (9), respectively.

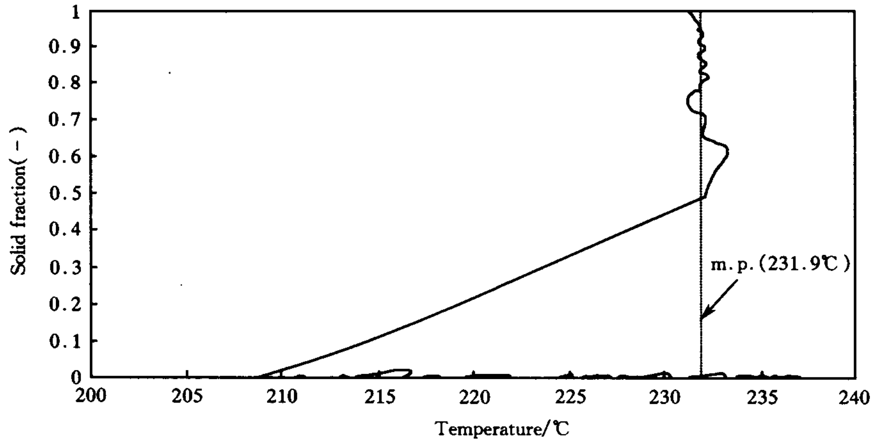

Fig.4 The relation between temperature and solid fraction for Zinc (cooling)

$$\chi_m = f_\alpha + f_\gamma \tag{7}$$

$$I = f_\alpha\chi_\alpha + f_\gamma\chi_\gamma \tag{8}$$

$$f_\alpha = \frac{(\chi_m - \chi_\gamma)}{(\chi_\alpha - \chi_\gamma)} \tag{9}$$

When a specimen kept in γ phase is suddenly put into a temperature where the phase transformation from γ to α takes place, the transitional fraction of α phase is given by Eq.(9). At the equilibrium where the phase transformation γ to α has finished, the value of χ_m and α phase fraction f_α are obtained as the $\chi = \chi_e$, which is the observed value at the equilibrium and $f_\alpha = \frac{b}{a+b}$, which is obtained from a phase diagram as shown in Fig.5. Then those are substituted into Eq. (9), χ_α is obtained by Eq. (10) and the value of χ_γ is given as the measured value of χ_m at $t = 0$.

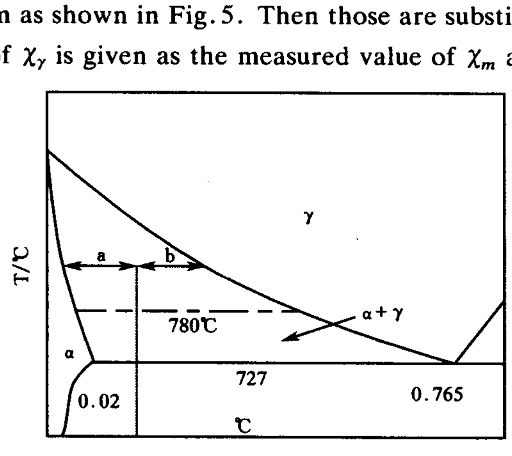

Fig.5 Fe-C phase diagram

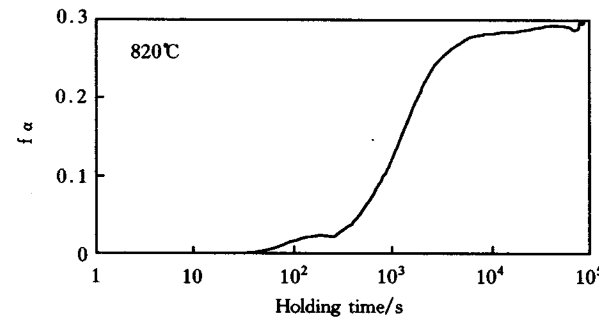

Fig.6 Transitional phase fraction of α in $\gamma - \alpha$ phase transformation.

$$\chi_\alpha = \frac{a+b}{b}\chi_e - \frac{a}{b}\chi_e \tag{10}$$

A specimen with a size of 2mm × 2mm × 0.5mm and 0.2C% steel encapsulated in a glass tube was kept at 950℃ for 30 min. under a magnetic field of 5T and then the temperature was quickly changed to 820℃ and kept there to induce the γ-α phase transformation under the magnetic field. The transitional phase fraction of f_α is shown in Fig. 6.

As the method developed here can be applied to in-situ measurement of various phase transformation in solid, liquid and gas phases, I hope it will provide the better and deeper understanding of phase transformations and reactions in the near future.

4. Crystal orientation in high magnetic field

4.1 Introduction

Recently, it has been found that the crystal orientation in materials can be controlled by imposition of the high magnetic field. This principle can be applied not only to magnetic materials but also to non-magnetic materials with asymmetric unit cells[12-22]. When materials are placed in a magnetic field, crystals exhibiting anisotropic magnetic susceptibility orient themselves to the direction of the maximum susceptibility parallel to the magnetic field direction.

In this chapter, the effect of a high magnetic field on the crystal orientation has been studied in two processes. In the first process using a slip casting operation, a crucible containing ceramic slurry was rotated under a high magnetic field to fabricate textured ceramics with one directional crystal orientation. In the second process, a green sample with some amount of oriented crystals which was initially introduced by the slip casting under a high magnetic field was sintered in a high magnetic field. In the sintering process, the effects of intensity of the magnetic field and the initially introduced amount of oriented crystals on the total crystal orientation in final products were studied.

4.2 Theory of crystal texture controlled by magnetic field theory

4.2.1 Magnetization energy

When a non-magnetic substance is magnetized in a magnetic field, the energy for magnetization of the substance is given by Eq. (11).

$$U = -\int_0^{B/\mu_0} M \mathrm{d}B_{in} \tag{11}$$

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

Let us consider ceramics of the crystal structure with a magnetic anisotropy, that is, the magnetic susceptibility is different in each crystal direction. The value of the magnetization energy given by Eq. (12) that is derived from Eq. (11), determines the preferred crystal direction depending on the magnetic susceptibility of each crystal axis and the crystal shape.

$$U = -\frac{\chi}{2\mu_0(1 + N\chi)^2} B^2 \tag{12}$$

where N is the demagnetization factor. Let χ_c and $\chi_{a,b}$ represent c-axis and a- or b-axis of a magnetic susceptibility, respectively. When, $\chi_c > \chi_{a,b}$, i.e. $U_c < U_{a,b}$, c-axis of crystals is the preferred axis in parallel to the direction of magnetic field. In contrast, when $\chi_c < \chi_{a,b}$, i.e. $U_c > U_{a,b}$, a-or b-axis of crystals is the preferred axis in parallel to the magnetic field, that is, c-axis of crystals aligns to all of