ELSEVIER

Materials Science and Engineering A 417 (2006) 281–286

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

# Processing and mechanical properties of a porous low carbon steel with a controlled porous structure by imposition of a static magnetic field

Yasumasa Chino [a,*], Mamoru Mabuchi [b], Kensuke Sassa [a], Shigeo Asai [c]

[a] *Materials Research Institute for Sustainable Development, National Institute of Advanced Industrial Science and Technology, 2266-98 Anagahora, Shimo-shidami, Moriyama-ku, Nagoya 463-8560, Japan*

[b] *Department of Energy Science and Technology, Graduate School of Energy Science, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan*

[c] *Department of Materials, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan*

Received in revised form 24 October 2005; accepted 4 November 2005

**Abstract**

Porous low carbon steels with a controlled porous structure were processed by imposition of a static magnetic field, and mechanical properties were investigated. Rotation behaviors of a low carbon steel in a static magnetic field was investigated by a theoretical analysis. The derived rotation time well agreed with the experimental result. The porous low carbon steel, which is the sintered green compact filled into a carbon die with a magnetic field, showed orientated structure parallel to the direction of a magnetic field. Compressive properties of the porous low carbon steel with a magnetic field showed higher collapse stress and higher densification strain compared with those of the porous low carbon steel without a magnetic field. Modifications of the compressive properties might be attributed to the oriented structure of the porous low carbon steel due to imposition of a static magnetic field.



*Keywords:* Porous metal; Magnetic field; Metal fiber; Low carbon steel; Mechanical properties

## 1. Introduction

Recently, there has been a considerable increase in interest for porous materials [1,2]. Porous metals are super-light metals exhibiting unique properties such as high energy absorbing [3]. It is important to deepen our understanding of mechanical properties of porous metals for the use of a porous metal in lightweight structural sandwich panel or in energy absorbing devices.

To date, the mechanical properties of porous materials have been extensively investigated [4–9]. These studies revealed that the porous materials exhibit a plateau region with a nearly constant follow stress. It has been demonstrated experimentally [10] and theoretically [3] that the flow stress in a plateau region is strongly affected by the density. Gibson and Ashby [3] analyzed the collapse stress (apparent yield stress) in a plateau region of a porous metal from the view point of bending of struts and they showed that the collapse stress of a porous material is proportional to the 3/2 power of density.

Natural porous materials have a variety of porous structure to match surrounding conditions such as applied loading. This suggests that mechanical properties of porous materials are strongly affected not only by the density, but also by the porous structure. Therefore, porous structure control might be one of a key technology for control of mechanical properties such as plateau stress.

In the present study, a new method for porous structure control of a porous metal by imposition of a static magnetic field has been proposed. A porous metal with a controlled porous structure is processed from sintering of ferromagnetic metal fibers. Metal fibers [11,12] are processed from machining by a lathe with a chatter vibration cutting tools. In the new method, ferromagnetic metal fibers are filled into a die under an imposition of a static magnetic field. Then, orientation of the ferromagnetic metal fibers parallel to the magnetic field occurs, and an oriented green compact is made in a die. A porous metal with porous structure control can be easily obtained by sintering the oriented green compact.

In the present study, at first, behaviors of a low carbon steel fiber under an imposition of a static magnetic field were investigated by a theoretical analysis and a model experiment. Next,

* Corresponding author. Tel.: +81 52 736 7461; fax: +81 52 736 7406.
*E-mail address:* y-chino@aist.go.jp (Y. Chino).

0921-5093/$ – see front matter 
doi:10.1016/j.msea.2005.11.015

compression properties of a porous low carbon steel with a controlled porous structure were compared with those of porous low carbon steel without a controlled porous structure.

## 2. Theoretical analysis

A ferromagnetic and polycrystalline fiber with a diameter of $d$ and a length of $l_f$ is placed under a static magnetic field with a magnetic flax density of $B$, and the fiber and the magnetic field are inclined at $\theta$ as shown in Fig. 1(a). In, Fig. 1(a), $T_{BF}$ is the torque caused by a magnetic shape anisotropy of the fiber, $T_E$ is the torque caused by a Lorentz force induced by an interaction of a rotational motion of the fiber and the magnetic field, $T_d$ is the torque caused by a viscous drag and $T_g$ is the torque caused by a gravity. The equation of rotational motion by the above torques is given by

$$I\frac{d^2\theta}{dt^2} + T_{BF} + T_E + T_d + T_g = 0 \tag{1}$$

$$I = \frac{\pi}{48} d^2 l_f^3 \rho \tag{2}$$

where $I$ indicates the moment of inertia for the fiber, $t$ the rotation time of the fiber and $\rho$ the density of the fiber. Since a distribution of the gravity acting on the fiber is symmetrical with respect to the fiber center, $T_g$ corresponds to zero. If $T_{BF}$ is much larger than $T_E$, and if the fiber is placed in a vacuum ($T_d = 0$), Eq. (1) is given by

$$I\frac{d^2\theta}{dt^2} + T_{BF} = 0 \tag{3}$$

Fig. 1(b) shows the coordinate system between the imposed magnetic field $H$ and the magnetization of the fiber $M$, where $y'$-axis defined as to be the direction of an easy magnetization axis with a demagnetizing factor $N_1$, and $z'$-axis is defined as to be the direction of a difficult magnetization axis with a demagnetizing factor $N_2$. Then, $T_{BF}$ and the relationship between $H$ and $M$ are given by [13]

$$T_{BF} = MH\,sin(\theta - \phi) \times V \tag{4}$$

$$M\,cos\,\phi = \mu_0 H \cos\theta - N_1 M \cos\phi \tag{5}$$

$$M \sin\phi = \mu_0 H \sin\theta - N_2 M \sin\phi \tag{6}$$

$$M = \chi H \tag{7}$$

where $\mu_0$ indicates the magnetic susceptibility in a vacuum ($4\pi \times 10^{-7}$ H/m), $\phi$ the angle between the $y'$-axis and the magnetization, $V$ the volume of the fiber and $\chi$ is the magnetic susceptibility.

By using Eqs. (4)–(6), $T_{BF}$ is given by

$$T_{BF} = \frac{\pi d^2 l_f}{4} MH \sin(\theta - \phi) \tag{8}$$

$$\tan\phi = \tan^{-1}\left\{\frac{1+N_1}{1+N_2}\tan\theta\right\}. \tag{9}$$

By using Eqs. (7)–(9), Eq. (3) is expressed as

$$\frac{d^2\theta}{dt^2} + \frac{6\chi^2\mu_0 H^2}{\rho l_f^2}(N_2 - N_1)\sin 2\phi = 0. \tag{10}$$

When the demagnetizing factors of a cylindrical fiber $N_1$ and $N_2$ are set to 0 and 1/2, respectively [14], a maximum difference in the angle between $\theta$ and $\phi$ is only $\pi/16$. Thus, it can be assumed that $\theta$ is the same as $\phi$. When the initial conditions are set to

$$\theta|_{t=0} = \theta_0 \tag{11}$$

$$\left.\frac{d\theta}{dt}\right|_{t=0} = 0 \tag{12}$$

the rotation time of a fiber is obtained as

$$t = \frac{l_f}{\chi H}\sqrt{\frac{\rho}{6\mu_0(N_2 - N_1)}}\int_0^{\theta_0}(\cos 2\theta - \cos 2\theta_0)^{-1/2}d\theta = \frac{l_f}{\chi B}\sqrt{\frac{\rho\mu_0}{6(N_2 - N_1)}}\int_0^{\theta_0}(\cos 2\theta - \cos 2\theta_0)^{-1/2}d\theta$$

$$\left(0 \le \theta_0 \le \frac{\pi}{2}\right). \tag{13}$$

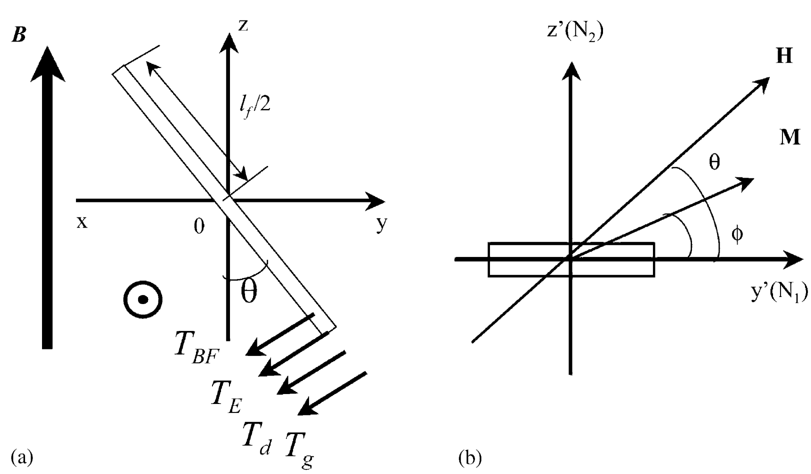


Fig. 1. System of a theoretical analysis, where (a) indicates the coordinate system between a ferromagnetic fiber and a magnetic flax density (b) the coordinate system between a imposed magnetic field and a magnetization of a ferromagnetic fiber.