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Magnetic properties of magnetic glass-like carbon prepared from furan resin alloyed with magnetic fluid

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ABSTRACT

Magnetic glass-like carbons that were heat-treated at different temperatures or were filled with different magnetic nanoparticle contents were prepared from furan resin alloyed with magnetic fluid (MF) or Fe_3O_4 powder in their liquid-phase states during mixing. Compared to the Fe_3O_4 powder-alloyed carbon, the MF-alloyed carbon has highly dispersed the nanoparticles, and has the excellent saturation magnetization and coercivity. It is implied that saturation magnetizations are related to changes in the types of phases for the nanoparticles and the relative intensities of X-ray diffraction peaks for iron and iron-containing compounds in the carbons. Additionally, the coercivities are possibly affected by the size and crystallinity of the nanoparticles, the relative amounts of iron, and the existence of amorphous compounds on the carbon surfaces.

1. Introduction

Bulk magnetic carbon materials, because of low density, high mechanical strength, high-temperature stability, and corrosion resistance, have potential as high performance materials such as electronic devices and magnetic shields etc. The materials have been prepared by various methods, such as the magnetic carbon films made from polyimide films alloyed with iron-based nanoparticles or complexes [1,2], the magnetic carbon spheres made from chelate resins alloyed with nickel- or cobalt-based nanoparticles or ions [3,4], and the magnetic graphite plates made by nickel- or iron-ion implantation [5,6]. However, the dispersion and content of magnetic nanoparticles, as well as the bulk formability, in the materials have been limited when prepared by these methods.

Non-graphitizable carbon, called glass-like carbon (GLC), containing many small closed pores with sizes of *ca.* 2–5 nm, and prepared from thermosetting resin derived from furan or phenol etc., exhibits excellent properties including high formability, high mechanical strength, high-temperature stability, corrosion resistance, and gas impermeability [7–16]. While GLC is already widely used in industrial applications in various fields for these properties, it is possibility to develop new applications for GLC in high performance materials. Magnetic fluid (MF) is a kind of colloid solution dispersing magnetic nanoparticles of the order of nanometers into water or organic solutions [17–19]. It is possible to prepare bulk magnetic carbon materials with high formability, high magnetic nanoparticle content, and high dispersal of magnetic nanoparticles into the matrix, by mixing raw matrix materials and raw additive materials in their liquid-phase states.

In this work, magnetic GLCs were prepared from mobile furfuryl-alcohol condensate alloyed with MF or Fe_3O_4-powder slurry in their liquid-phase states during mixing in order to develop new applications in high performance materials. The magnetic properties of the carbons prepared using a range of heat-treatment temperatures and with varying relative nanoparticle contents were investigated using a vibrating sample magnetometer (VSM). Additionally, nanoparticle dispersion in the carbons was observed using scanning electron microscopy (SEM), and changes in the magnetic properties of the carbons were discussed by the analyses of X-ray diffraction (XRD) and field-emission SEM (FE-SEM).

2. Experimental

Furan resin, which was used as the precursor to glass-like carbon (GLC), was derived from mobile furfuryl-alcohol condensate (Hitafuran302, Hitachi Chemical Co., Ltd.: furan resin) as shown elsewhere [20] and cut into $2{\times}2{\times}2$ or $10{\times}10{\times}2\ mm^3$ sized pieces. GLCs were prepared by heat treatment (carbonization) of the resins at 800, 1000, 1200, or 1500 °C for 30 min in Ar flow. Magnetic resins with nanoparticle contents of 1.0, 2.5, or 5.0 wt% were prepared by

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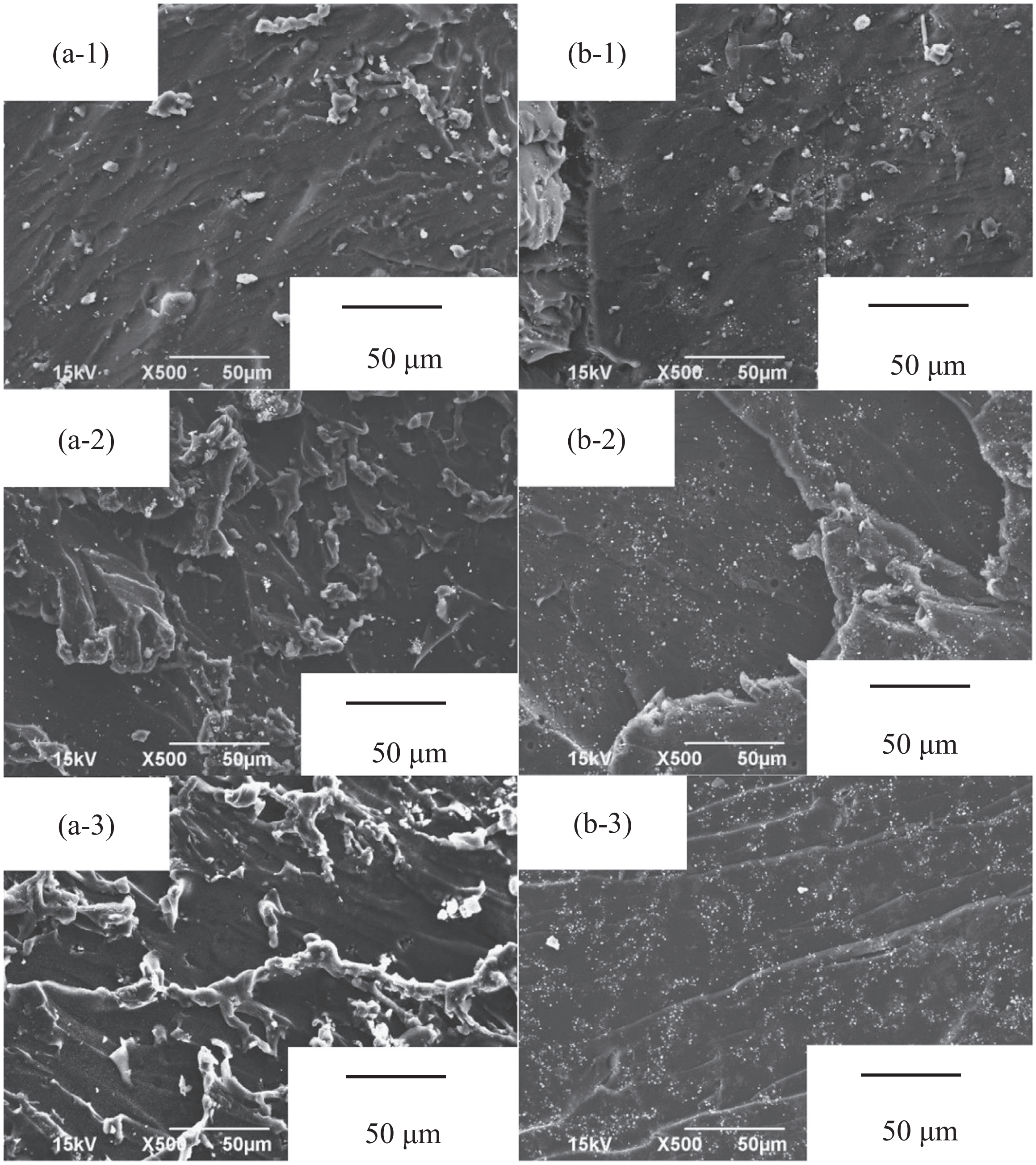

Fig. 1. SEM images of the fractured surfaces, after being heat-treated at 1000 °C, of the MF-alloyed GLCs with nanoparticle contents of (a-1) 1.0, (a-2) 2.5, or (a-3) 5.0 wt%, and of the Fe_3O_4 powder-alloyed GLCs with nanoparticle contents of (b-1) 1.0, (b-2) 2.5, or (b-3) 5.0 wt%. The small white point-like dots in black carbon matrix are the magnetic nanoparticles.

mixing either water-based magnetic fluid (MF; M-300, SIGMA HI-CHEMICAL Inc.) or Fe_3O_4 powder (95+% purity, Wako Pure Chemical Industries, Ltd.) slurry into the condensate in liquid-phase states. Then, the magnetic resins filled with a nanoparticle content of 1.0 wt% were carbonized at 800, 1000, 1200, or 1500 °C, and those with 2.5 or 5.0 wt% were carbonized at 1000 °C.

In order to confirm dispersion of the nanoparticles, the fractured surfaces of the carbons were observed with SEM (JSM-5600LANV, JEOL, Ltd.) at a voltage of 15 kV. The saturation magnetizations (M_s) and coercivities (H_c) of the carbons were estimated from magnetization *versus* magnetic field curves (M-H curves) using a VSM (TM-VSM1015-CRO-T, TAMAGAWA Co., Ltd.). The VSM measurements were carried out by cycling the magnetic field between −10 and +10 kOe (1 Oe=$10^3/4\pi$ A/m) at room temperature. XRD (RINT-Ultima III, Rigaku Co.) measurements were performed to observe changes in the types of phases for the nanoparticles and the relative intensities of peaks for iron and iron-containing compounds in the carbons, using Cu Kα radiation at 40 kV and 40 mA accelerating voltage and current, respectively. The size and crystallinity of the nanoparticles on the surfaces of the carbons were observed with an FE-SEM (SU8000, Hitachi High-Technologies Co.) operating at a voltage of 15 kV, and the existence and relative amounts of iron on the surfaces