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Critical current densities in Ag-added bulk MgB_2

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ABSTRACT

In previous studies, we found that bulk MgB_2 contained numerous voids in various shapes and sizes. With the aim of improving the critical current density as well as the mechanical performance of the disk-shaped MgB_2 bulk superconductors, we added Ag and optimized the processing conditions. The samples with varied Ag content from 0, 2, 4, 6, to 10 wt% were synthesized in pure Ar atmosphere. Microstructural observation by scanning electron microscopy confirmed that metallic Ag particles are embedded in the void regions. Furthermore, atomic force microscopy indicated that silver-based MgB_2 particles are of nanometer size. As a result, the critical current density (J_c) values were improved with Ag addition as compared to pure MgB_2 bulk. The sample with 4 wt% Ag addition exhibited the highest J_c of 293 kA/cm^2 at 20 K and self field. The respective J_c values at 10 K were 400 kA/cm^2, 300 kA/cm^2, and 100 kA/cm^2 in self field, 1 T and 2 T. These values are the highest record values so far reported in bulk MgB_2 materials.

1. Introduction

Ominous progress has been made in the development of MgB_2 materials processing, characterization, and applications [1–6]. The superconducting transition temperature of MgB_2 is significantly lower than that of $YBa_2Cu_3O_y$ "Y-123", instead, MgB_2 benefits from BCS-like superconducting features a large coherence length which allows a better Josephson junction fabrication. The high critical temperature within intermetallic superconductors indicates that low cooling cost enables a cheaper technology, the high critical current density (J_c) achievable in the polycrystalline state which leads to facilitated cable production for the power industry, all of which makes these materials very promising candidates for several industrial applications including the next generation of medical devices, electrical power systems, transpiration systems and powerful super-magnets operating at around 20 K [7–10]. For superconducting super-magnet applications, it is required to produce good quality, bulk MgB_2 material with high J_c and an acceptable mechanical performance. To improve the critical current density of the MgB_2 material, a variety of processing techniques have been developed including chemical doping [11], refining of the initial particle size by ball milling [12], and irradiation [13]. As a result, the transport J_c values at liquid helium temperature and 10 T reached the level of 10^5 A/cm^2 for Si-doped MgB_2 samples. Similar improvements were also observed with additions of carbon, boron carbide, carbon nanotubes, carbohydrates or hydrocarbons, graphene oxide, Ni–Co–B nanoparticles [14–20]. However, the critical current density values of MgB_2 materials still need a further improvement for high magnetic field applications. One of the main obstacles for this is the fact that MgB_2 bulks or wires produced by an in-situ process usually are highly porous. Surprisingly, the density of bulk MgB_2 material is typically only 50% of the theoretical density [21]. The resulting microstructure with high porosity may reduce the mass density, the super-current carrying area and therefore J_c as well as the mechanical performance. Recent results showed that the high J_c and the trapped field values were achieved in samples prepared with a simple solid state reaction when the processing conditions were properly optimized. A trapped field value of 1.51 T at 20 K was achieved in MgB_2 samples of 20 mm diameter and 7 mm thickness when sintered at 775 °C, reflecting the high pinning performance and the homogeneous microstructure [21]. The simple sintering route is attractive for mass production of bulk MgB_2 materials for a wide range of commercial applications. However, microstructural analysis by scanning electron microscopy indicated that the MgB_2 matrix contains numerous voids in various shapes and sizes, which may reduce the mass density and the J_c values. The Ag addition to MgB_2 will be one of the solutions to overcome this problem. In addition, less work has been reported on the role of Ag addition in the synthesis of bulk MgB_2 materials [22]. Therefore, a study on Ag addition combined with optimization of processing

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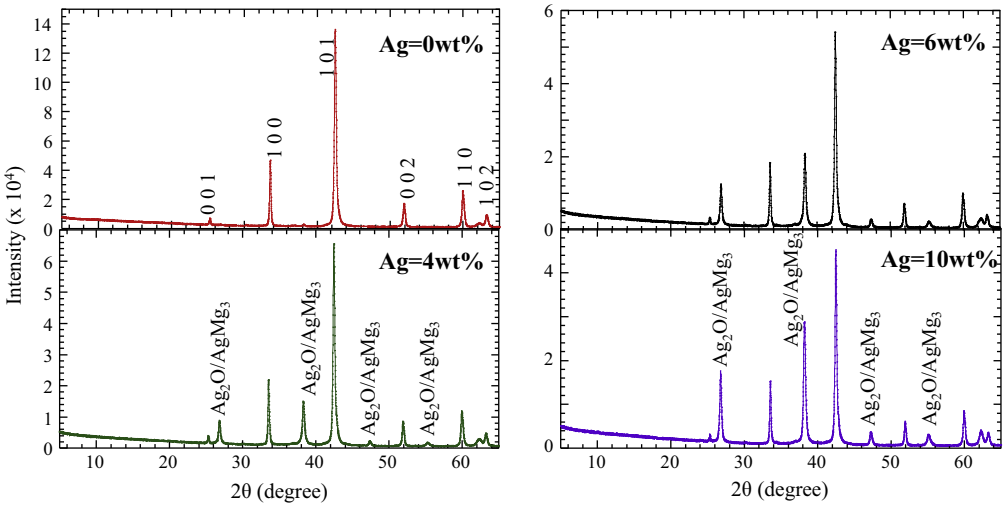

Fig. 1. X-ray diffraction patterns of bulk MgB_2 sample with 0 wt%, 4 wt%, 6 wt%, 10 wt% Ag, sintered at 775 °C for 3 h in Ar atmosphere.

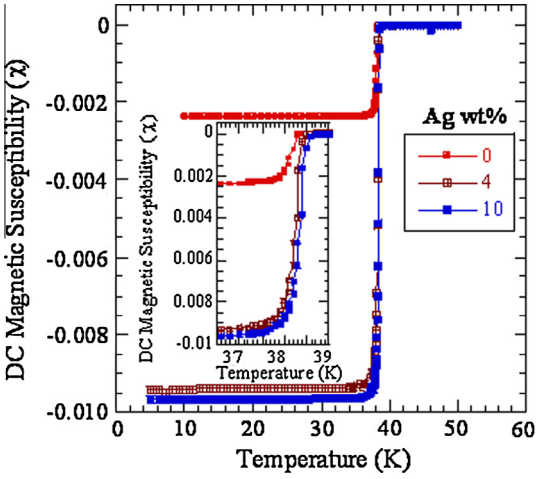

Fig. 2. Temperature dependence of magnetic susceptibility for MgB_2 sample with 0 wt%, 4 wt%, and 10 wt% Ag, sintered at 775 °C for 3 h in Ar atmosphere.

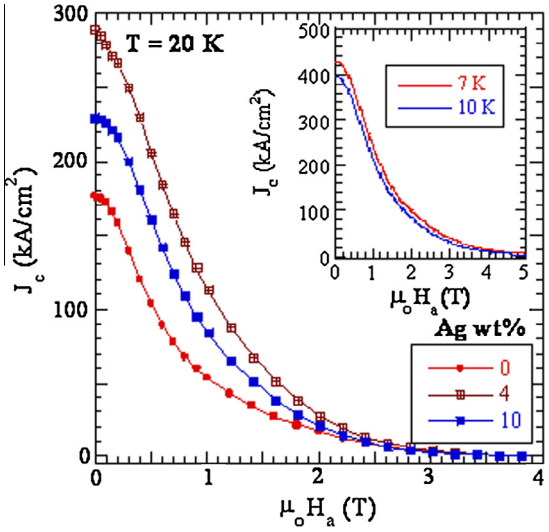

Fig. 3. Field dependence of the critical current densities at $T = 20$ K for MgB_2 sample with 0 wt%, 4 wt%, and 10 wt% Ag, sintered at 775 °C for 3 h in Ar atmosphere. The inset presents the 7 K critical current performance for the MgB_2 materials with 4 wt% of Ag.

conditions for MgB_2 bulk materials is crucially important for a further improvement of J_c.

In the present paper, we report on the microstructure and superconducting properties of the Ag-added MgB_2 materials fabricated with a simple sintering method. Scanning electron microscopy and atomic force microscopy indicated that large silver particles are trapped in the pore and silver based nanometer sized Mg particles are dispersed in the MgB_2 matrix. Further, magnetization measurements showed that Ag addition was effective in achieving high critical current density values in bulk MgB_2 materials.

2. Experiment details

The bulk polycrystalline MgB_2 samples were fabricated by using in-situ solid state reaction. High-purity commercial powders (Furu-uchi Chemical Corporation, Japan) of Mg metal (99.9% purity, 200 meshes) and amorphous B powder (99% purity, 300 meshes) were mixed in a nominal ratio of Mg:B = 1:2. High purity metallic Ag with contents of 0, 2, 4, 6, and 10 wt% was added to the bulk MgB_2 material. The starting powders were thoroughly ground in a glove box under nitrogen atmosphere. The powder mixture was pressed into pellets 20 mm in diameter and 7 mm in thickness using a uni-axial pressing machine. The consolidated pellets were then wrapped in tantalum foils and subjected to the heat treatment in Ar atmosphere in a tube furnace. The samples were heated to the target sintering temperature of 775 °C and kept there for 3 h in flowing argon gas. Finally, the temperature was lowered to room temperature at a cooling rate of 100 °C/h.

The constituent phases of the samples were identified with a high-resolution automated X-ray powder diffractometer (RINT2200), using Cu Kα radiation generated at 40 kV and 40 mA. The microstructure of these samples was studied with a scanning electron microscope (SEM) and an atomic force microscope (AFM) operating in the tapping mode (Veeco/DI Nanoscope IV). Chemical compositions were analyzed by energy dispersive X-ray spectroscopy (EDX).

Small specimens with dimensions of $1.5 \times 1.5 \times 0.5$ mm^3 were cut from bulk MgB_2 samples and subjected to the measurements of the critical temperature (T_c) and magnetization hysteresis loops (M–H loops) in applied magnetic fields from −1 to +5 T at temperatures of 20 K using a SQUID magnetometer (Quantum Design, model MPMS5). The magnetic J_c values were estimated based on the extended Bean critical state model using the relation

$$J_c = 2\Delta m/[a^2 d(b - a/3)] \quad (1)$$