Available online at www.sciencedirect.com
ScienceDirect
Scripta Materialia 61 (2009) 557–560
Scripta MATERIALIA
www.elsevier.com/locate/scriptamat

The microstructure of Fe–Ga powders and magnetostriction of bonded composites

Jiheng Li, Xuexu Gao,* Jie Zhu, Juncheng Jia and Maocai Zhang

State Key Laboratory of Advanced Metals and Materials, University of Science and Technology, Beijing 100083, China

Received 7 January 2009; revised 12 April 2009; accepted 13 April 2009
Available online 16 April 2009

Spherical Fe–Ga particles were prepared by gas atomization. The Ga concentration of gas-atomized particles approached the nominal composition of $Fe_{81}Ga_{19}$. Most size fractions of particles had a polycrystalline structure. The main A2 phase and a DO_3 phase emerged in the as-atomized powders. The $L1_2$ phase appeared in the annealed powders. Many single crystals were obtained due to grain growth during the thermal process. The maximum saturation magnetostriction of 6.4×10^{-5} was obtained in the composite containing the annealed powders.

Keywords: Fe–Ga alloy; Gas atomization; Powders; Magnetostriction

Fe–Ga (Galfenol) alloys have received considerable attention due to their large saturation magnetostriction in low applied fields and high mechanical strength, and thus their potential application in magnetostrictive actuators and sensors [1–4]. Magnetostrictive composite materials such as Terfenol-D are composed of magnetostrictive particles dispersed within a polymer matrix and present good advantages over the monolithic magnetic material; the binder creates an insulating layer between the particles, which increases the receptivity and reduces eddy current losses at high frequencies [5]. To date, there have been few studies on powder preparation methods from Fe–Ga alloys and the magnetostriction of bonded composites.

Hong et al. [6] reported that spherical Fe–Ga particles were prepared by spark erosion in liquid Ar, and a maximum magnetostriction of 5.35×10^{-5} was obtained in the composites prepared by mixing particles with 48 vol.% epoxy and curing in a magnetic field. Gaudet et al. [7] were the first to investigate Fe–Ga powders prepared by mechanical alloying. Their results suggested the presence of a disordered body-centered cubic (bcc) A2 phase with no indication of an ordered DO_3 phase. However, Gaudet et al.'s study did not report bonded Fe–Ga magnetostrictive composites or their magnetostrictive performance. In this work, Fe–Ga powders were prepared by gas atomization, and to our knowledge this is the first investigation of Fe–Ga powders prepared by this method. The microstructure of as-atomized and annealed Fe–Ga powders and magnetostriction of composites were investigated. $L1_2$ phase, which is very difficult to form in annealed Fe–Ga bulk samples, was observed in the $Fe_{81}Ga_{19}$ particles annealed at 800 °C. The maximum magnetostriction value of 6.4×10^{-5} was obtained in the $Fe_{81}Ga_{19}$ composite prepared by mixing the <25 μm annealed powders and epoxy.

$Fe_{81}Ga_{19}$ alloy ingots, weighing roughly 1000 g, were prepared from pure Fe (99.95% purity) and Ga (99.995% purity) by induction melting under an argon atmosphere. The powders, of three sieve sizes, <25, 25–40 and 40–75 μm, were prepared by gas-atomizing $Fe_{81}Ga_{19}$ ingots in an Ar atmosphere. The phases in the powders were identified by X-ray diffractometry (XRD) and differential thermal analysis (DTA). Microstructures of the as-atomized and annealed powders were examined by scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS) and transmission electron microscopy (TEM). The powders were then mixed with 3.0 wt.% epoxy binder. The mixed powders were compacted at a pressure of 271 MPa. In order to align the powders, compaction was also carried out under an applied magnetic field of 2 T, the direction of which was perpendicular to that of pressing. The magnetic field was applied by electromagnet. Composites with high mechanical strength were finally obtained by

* Corresponding author. Tel.: +86 10 62334343; fax: +86 10 62334327; e-mail: gaox@skl.ustb.edu.cn

1359-6462/$ - see front matter © 2009 Published by Elsevier Ltd. on behalf of Acta Materialia Inc.
doi:10.1016/j.scriptamat.2009.04.019

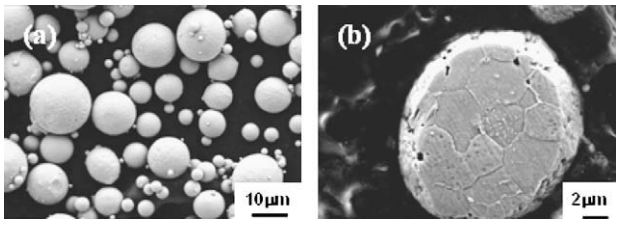

Figure 1. SEM micrographs showing $Fe_{81}Ga_{19}$ as-atomized powders. (a) Typical particle morphology and (b) cross-section of a polycrystalline particle.

curing at 170 °C for 1 h. The shape of the composites was mainly cylindrical, with a diameter of 12 mm and a height of 18 mm. The mechanical properties of the composites were identified by the static compress test using a 100 kN-electron universal testing machine. The magnetostriction was measured by strain gauging.

Figure 1(a) shows an SEM micrograph of <25 μm as-atomized powders. It can be seen that the spherical Fe–Ga particles were prepared by gas atomization. Cross-sections of the particles, shown in Figure 1(b), were obtained by mechanically polishing the particles mounted in bakelite. Most of the particles were polycrystals, as shown in the figure. The Ga concentration was measured by EDS, and in the 25–40 μm particles was determined to be 18.6 at.%, 0.4 at.% Ga being lost in the gas atomization process.

The XRD spectra of the starting alloy and the as-atomized powders with different particle sizes are shown in Figure 2(a). It can be seen that the spectrum of the $Fe_{81}Ga_{19}$ starting alloy was consistent with a disordered bcc α-Fe structure, while the satellite peak at 43.692° may indicate the presence of some ordered DO_3 phase in the powders prepared by gas atomization. Srisukhumbowornchai and Guruswamy [8] have suggested that all peaks corresponding to the DO_3 and A2 phases overlap, except for the weak satellite peaks corresponding to the ordered structure. DTA was employed in order to determine the possible presence of some DO_3 phase. Endothermic reactions were detected at about 617 °C, as shown in Figure 2(b), which may correspond to the $A2 \rightarrow A2 + DO_3$ reaction. Ikeda et al. [9] have pointed out that the same transition occurred at about 630 °C in Fe–21.5 at.% Ga alloys. From both XRD and DTA, DO_3 phase was found be present in the powders prepared by gas atomization, which suggests that the quenching rate was not fast enough to maintain only the high temperature disordered A2 structure.

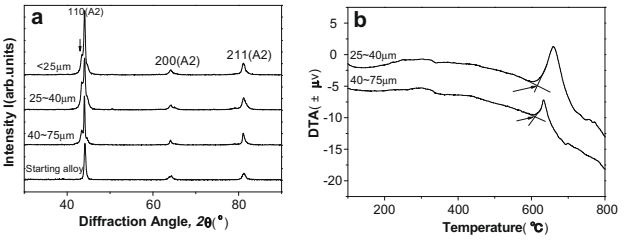

Figure 2. (a) XRD spectra of as-atomized powders with different particle sizes and starting alloy and (b) DTA curves of powders.

Lograsso et al. [10] have reported that the quenching treatment after heat treatment at 800 °C for 4 h was found to be successful in preventing the formation of DO_3 phase in single crystal Fe–19 at.% Ga alloys. In our work, heat treatment was done in an encapsulated quartz tube under an argon atmosphere according to the following protocol: 800 °C for 4 h and quenching into water, 800 °C for 4 h and furnace cooling, 800 °C for 8 h and furnace cooling. Figure 3(a–c) presents the XRD spectra of the powders, following each of the thermal treatments. It can be seen that, as expected, the formation of DO_3 phase was prevented in the powder after heat treatment at 800 °C for 4 h and water quenching, but more new peaks were observed in the pattern from this sample. These new peaks have been indexed as coming from the Fe_3Ga $L1_2$ phase. The $L1_2$ phase was also observed in the furnace-cooled samples. It was a surprise to observe the $L1_2$ phase in the annealed samples. This may indicate a structural transformation from A2 and DO_3 to $L1_2$ during the thermal treatment process. $L1_2$ phase was also observed in an Fe–27.5 at.% Ga rod, directionally cast and annealed at 1100 °C for 4 h, 500 °C for 72 h and 350 °C for 266 h [8]. It is thus believed that the $L1_2$ phase is very difficulty to form. Compared with the bulk sample of Fe–Ga alloy, the rule of structure transformation in Fe–Ga powers may be different, resulting in a structural transformation from A2 and DO_3 to $L1_2$ within the region of stability of the A2 phase, as shown in the phase diagram of

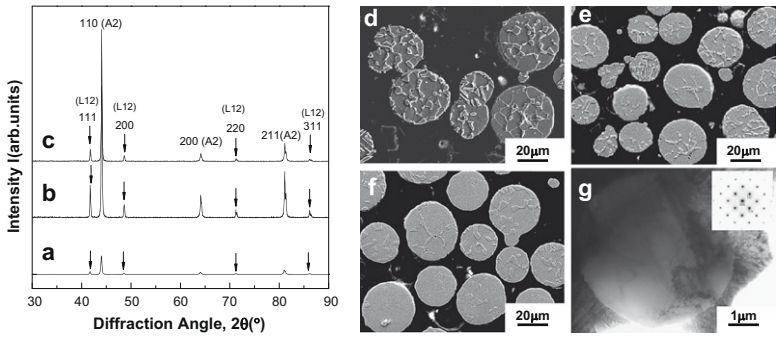

Figure 3. XRD spectra of <25 μm powders annealed at 800 °C for (a) 4 h, water quenched; (b) 4 h, furnace cooled; and (c) 8 h, furnace cooled. SEM micrographs showing cross-section of powders annealed at 800 °C for (d) 4 h, water quenched; (e) 4 h, furnace cooled; and (f) 8 h, furnace cooled. (g) BF TEM image of a single crystal particle and the corresponding EDP.