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Effect of thermal history and gallium content on magneto-mechanical properties of iron gallium alloys

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Abstract

Thermo-mechanical and magneto-mechanical properties were studied for iron substituted with 17.5, 19.1 and 20.5 at.% gallium quenched from 1000 °C and subsequently heated to 400 °C and slow-cooled. A phase change was observed in the 19.1 and 20.5 at.% Ga quenched samples upon heating. X-ray diffraction studies on the single crystal samples showed that the phase change observed was due to the precipitation of $D0_3$ upon heating from the quenched state. Magneto-mechanical characterization showed that the presence of ordered $D0_3$ phase in the slow-cooled 19.1 at.% Ga sample reduced the saturation magnetostriction in comparison to the quenched sample of same composition. The magneto-mechanical properties of both the quenched and slow-cooled 17.5 at.% Ga samples were similar owing to the presence of only the disordered A2 phase in both these samples.

Keywords: Fe–Ga alloy; Galfenol; Magnetostriction; Thermal expansion; X-ray diffraction; Structural determination

1. Introduction

Iron-gallium alloys (Galfenol) exhibit magneto-mechanical coupling making them attractive for sensor–actuator application. The magnetostrictive phenomenon of interest in Galfenol occurs along the ⟨1 0 0⟩ crystal direction, with the maximum magnetostriction (Fig. 1) occurring for 17 at.% Ga (furnace cooled sample) and 19 at.% Ga (quenched sample) substitution in BCC α iron [1,2]. The magnetostriction increase over that of pure iron occurs because of an increase in magnetoelastic coupling b_1 due to short range ordering between the Ga–Ga atoms in BCC α iron with randomly substituted gallium atoms (A2 structure) [3]. Further increase in gallium substitution induce long range ordering which produces $D0_3$ and B2 structures (Fig. 2) that mitigate the magnetostriction [4]. Water quenching the alloy from 800 °C or above preserves the A2 structure and allows an enhanced magnetostriction to be obtained up to ∼20 at.% Ga substitution [5].

This work investigates the thermo-mechanical and magneto-mechanical properties and their dependence on the thermal history of Fe–Ga alloys with 17.5–20.5 at.% Ga. The thermo-mechanical characterization from 25 to 400 °C (below the $A2/D0_3$ transition temperature of 700 °C [4]) was motivated by the fact that Galfenol can possibly be used as a structural smart material which can be adhered to other metals by thermally induced metal joining processes. The effect of quenching and slow-cooling the material from 800 °C or above on the material properties has been investigated earlier which can be useful for studies related to welding of Galfenol [1,5]. The temperature range used in the present work can be useful to understand the nature of residual stresses that develop due to coefficient of thermal expansion (CTE) mismatch during soldering or brazing. Magneto-mechanical characterization was conducted to evaluate the extent of difference in magneto-mechanical behavior before and after a quenched sample is exposed to temperatures achieved at low-temperature soldering or brazing. High resolution X-ray diffraction was performed to detect the phases in the quenched and slow-cooled samples.

2. Sample preparation

All samples are single crystals and were obtained from the Materials Preparation Center at the Ames Laboratory, Iowa [6].

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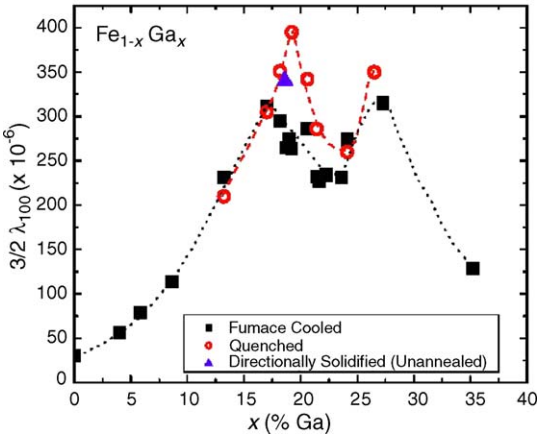

Fig. 1. Magnetostriction vs. at.% Ga in Fe–Ga alloys [2].

The samples in this work have been classified as "quenched" or "slow-cooled". The quenched samples were prepared by annealing them at 1000 °C for 4 h and then quenching them in water at room temperature. After performing the first set of experiments, these quenched samples were heated in a programmable oven from 25 to 400 °C at the rate of 5 °C/min and then were allowed to slow-cool inside the furnace back to room temperature.

Energy dispersive spectroscopy (EDS) was performed on the samples to find the composition. The set of samples chosen for this work have a composition of 17.5 (±0.3), 19.1 (±0.6) and 20.5 (±0.2) at.% Ga which correspond to the region around the first peak in magnetostriction in Fig. 1. No significant change in composition was observed due to the effect of thermal processes.

3. Experiments

3.1. Thermo-mechanical analysis

The thermo-mechanical analysis was performed on samples having 17.5, 19.1 and 20.5 at.% Ga using a Perkin-Elmer thermo-mechanical analyzer (TMA). The samples were 6.31 mm in diameter by 8–16 mm in length with the ⟨0 0 1⟩ crystallographic direction oriented along the longitudinal axis of the samples. A static load of 2 mN was initially applied and the quenched samples were then heated in a closed furnace, from 25 to 400 °C at the rate of 5 °C/min. The change in probe position (corresponding to sample length) with temperature was noted. The samples were slow-cooled to room temperature and then the same heating/cooling cycle was repeated.

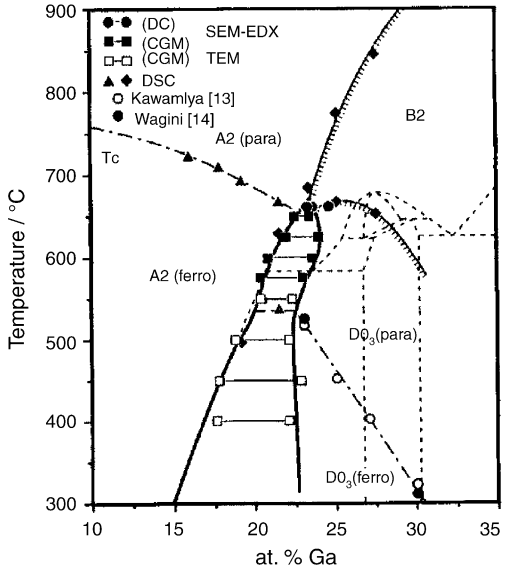

Fig. 2. Metastable Fe–Ga phase diagram [4].

3.2. X-ray diffraction

Discs of 6.31 mm diameter and 1 mm thickness were cut out from the samples with 17.5, 19.1 and 20.5 at.% Ga. One set of discs was cut from the quenched sample and another set after slow-cooling them from 400 °C. All the disks were fine-oriented with ⟨0 0 1⟩ normal to the {1 0 0} surface within 0.5° and were polished with 1 μm diamond followed by etching with a dilute nitric acid/water solution. X-ray diffraction studies were conducted in a Panalytical X'Pert diffractometer with Cu Kα radiation at 45 kV and 40 mA. The scans were performed over a 2θ range of 20–90° using a scan step of 0.02° and a divergence slit of 1/32°.

3.3. Magneto-mechanical analysis

The magneto-mechanical characterization of quenched and slow-cooled samples having 17.5 and 19.1 at.% Ga was performed using a thermally controlled transducer [7]. The samples were 6.31 mm in diameter by 25–30 mm in length with the ⟨0 0 1⟩ crystallographic direction oriented along the longitudinal axis of the samples. The temperature of the sample was maintained at 23 °C using a water-cooling system. A Hall effect sensor measured the magnetic field (H) while a pickup coil wound around the sample measured the magnetic induction (B). Two strain gages placed along the length of the sample were used to measure the strain (λ). The strain gages were attached diametrically opposite to each other so as to nullify any strain component due to bending. A free-hanging weight assembly was used to apply the compressive pre-stress on the sample. The magnetic and magneto-mechanical responses of the samples were measured under quasi-static 0.01 Hz, 75 kA/m amplitude sinusoidal applied magnetic field conditions for two cycles. Prior to each test, the samples were stabilized at a compressive stress of 30 MPa and then demagnetized over 167 cycles using a 1 Hz sinusoidal field which underwent a 5% geometric decay every 1.5 cycles from an initial amplitude of 90 kA/m. The data was collected using a computer-controlled system at 50 scans/s.

4. Results and discussion

4.1. Thermo-mechanical analysis

The coefficient of thermal expansion (CTE) can be calculated from Eq. (1):

$$\mathrm{CTE} = \frac{\Delta l}{l \Delta T} \tag{1}$$