Materials Science & Engineering A 639 (2015) 370–373

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Rapid communication

Dual-reinforcement ($TaC_{particle}+TaC_{dendrite}$)/FeGa magnetostrictive composites

Aili Sun, Jinghua Liu*, Cheng Bao Jiang*

Key Laboratory of Aerospace Materials and Performance (Ministry of Education), School of Materials Science and Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 26 March 2015
Received in revised form
8 May 2015
Accepted 10 May 2015
Available online 18 May 2015

Keywords:
Fe–Ga alloy
Magnetostriction
Grain refinement
Secondary-phase reinforcement
Composite

ABSTRACT

Remarkable enhancements in tensile strength (~625 MPa) and elongation ratio (~1%), being three and five times, respectively, as large as those of the binary $Fe_{81}Ga_{19}$ alloy, were obtained *in situ* dual-reinforcement ($TaC_{particle}+TaC_{dendrite}$)/$Fe_{81}Ga_{19}$ magnetostrictive composites due to grain refinement and secondary-phase reinforcement.

1. Introduction

As a magnetostrictive material, the rare-earth-free Fe–Ga (Galfenol) alloys exhibit merits of high magnetostriction, low saturation field, and high permeability [1–3]. A large magnetostriction up to 400 ppm at low magnetic fields has been found in single crystal state [4]. Great potential of Fe–Ga alloys have been shown for key smart materials used in actuators, sensors, damping devices, and positioning devices [5,6]. However, Fe–Ga alloys show an intrinsic brittleness due to the covalent bonding between Ga and Fe atoms, which leads to brittle fractures with relatively low tensile strength and low elongation ratio [7,8]. The study on the mechanical properties of Fe–Ga alloys thus becomes an increasingly important subject in practical load-bearing engineering applications. In recent years, great efforts have been devoted to the as-rolled Fe–Ga-based sheets with desired highly-orientated textures [9–11]. The textured sheets potentially show high magnetostriction near the values of singe crystals but have small eddy current losses, low producing costs, and simple preparing processes. During the rolling deformation, however, significant cracking usually develops along grain boundaries of the sheets even at high temperatures [12,13], which largely hinders the development of textured Fe–Ga-based thin sheets. Therefore, more ways should be found to improve the mechanical properties of Fe–Ga alloys.

It has been reported that the ternary additions can improve the mechanical properties and rolling ability of Fe–Ga-based alloys [8,14,15]. Meanwhile, adding of small-size interstitial B, C and N atoms is also beneficial to the magnetostriction of Fe–Ga alloys [16,17]. It has been confirmed that introducing the ternary additions is a simple and effective method to tailor the desired properties of Fe–Ga alloys.

In this work, we selected TaC carbide, a cubic phase with a high melting point, as the new ternary addition to study the phase distribution and mechanical properties of $Fe_{81}Ga_{19}$ alloy. It was found that, in the new materials the added TaC phase exists as nuclei for heterogeneous nucleation, rod-shaped particles and dendrite clusters within the grain matrix or at the grain boundaries, which results in *in situ* ($TaC_{particle}+TaC_{dendrite}$)/$Fe_{81}Ga_{19}$ composite alloys. Based on both the grain refinement and secondary phase distribution, the mechanical strength and elongation ratio of $Fe_{81}Ga_{19}$ alloy were remarkably enhanced, with the magnetostriction behavior being not deteriorated.

2. Experimental procedures

$(Fe_{81}Ga_{19})_{100-x}(TaC)_x$ ($x=0$, 0.5, and 1.0) ingots with a weight of ~400 g and a diameter of 65 mm were prepared by arc melting high-purity Fe (99.99%), Ga (99.99%) and TaC powders under argon atmosphere. Each ingot was melted four times to assure the homogeneity. The ingots were annealed at 1373 K for 3 h and then

* Corresponding authors. Tel.: +86 10 82338780; fax: +86 10 82338200.
E-mail addresses: lud@buaa.edu.cn (J. Liu), jiangcb@buaa.edu.cn (C.B. Jiang).

http://dx.doi.org/10.1016/j.msea.2015.05.021
0921-5093/

slowly cooled to room temperature. X-ray diffraction (XRD) measurements were performed by using a Rigaku D/Max2200 PC diffractometer with Cu-K_α radiation. The magnetostriction was measured using the standard strain gauge with the magnetic field parallel to the gauge on the sample with dimensions of $14.00 \times 7.00 \times 6.00\ mm^3$. Five tensile samples of each alloy with gauge length of 26 mm were cut from the center of the alloys. The tensile samples were subjected to room-temperature tensile test using a computer-controlled Instron-8801 testing machine with a constant velocity of $0.075\ mm\ min^{-1}$. The scanning electron microscopy (SEM, Hitachi S-4800) was used to investigate the microstructure morphology, phase distribution and fracture surfaces of the tensile samples.

3. Results and discussion

Fig. 1 shows the XRD patterns of $(Fe_{81}Ga_{19})_{100-x}(TaC)_x$ ($x=0$, 0.5, and 1.0) alloys. The main phase with bcc A2 structure was observed in binary Fe–Ga alloy, which is in good agreement with the Fe–Ga phase diagram [18] and previous studies [11,15,17]. In TaC-added alloys, the diffraction peaks of fcc TaC phase appear, showing an increasing diffraction intensity with increasing TaC content. A slow step-scan XRD pattern between 33° and 42°, as shown in left inset of Fig. 1, gives a more clear diffraction of fcc TaC phase. It is suggested that the desired TaC phase has formed in the studied $Fe_{81}Ga_{19}$-based alloys. For the convenience in further investigation, the morphology of starting TaC powder, which consists of spherical particles with an average diameter of 400 nm, was shown in right inset of Fig. 1.

Fig. 2a–c shows the optical micrographs of the microstructure in studied alloys. For $Fe_{81}Ga_{19}$ alloy (Fig. 2a), the equiaxed grains with straight and narrow boundaries are presented, with an average grain size of about 650 μm. After adding TaC, the grains are refined remarkably. For $x=0.5$ (Fig. 2b), the grain size is decreased to 550 μm. When the TaC content reaches $x=1.0$ (Fig. 2c), the grains are further reduced to about 350 μm, showing dendritic sub-structures in each grain. The relation between the grain size and TaC content is plotted in Fig. 2d, which gives a clear effect of grain refinement by adding TaC phase.

In order to probe the TaC phase distribution, the backscattering electron (BSE) imaging was performed on SEM. In TaC-free $Fe_{81}Ga_{19}$ alloy (Fig. 2e), no secondary phase can be seen in alloy grains. In alloy with $x=0.5$ (Fig. 2f), the high-density rod-shaped particles with bright contrast disperse within the grains and at the grain boundaries. The energy-dispersive spectrometry (EDS) analysis indicated that these particles are rich of Ta element (it is

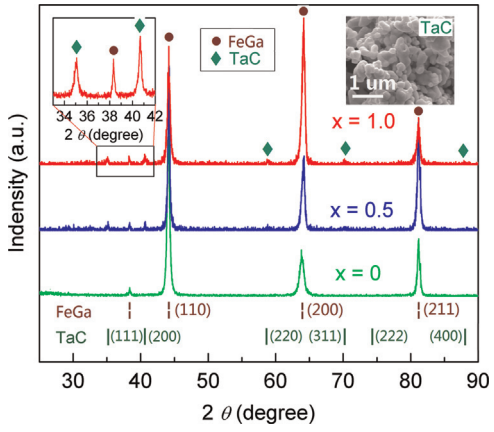

Fig. 1. XRD patterns of the studied alloys. Left inset shows the slow step-scan XRD pattern between 33° and 42°. Right inset shows the morphology of TaC powders.

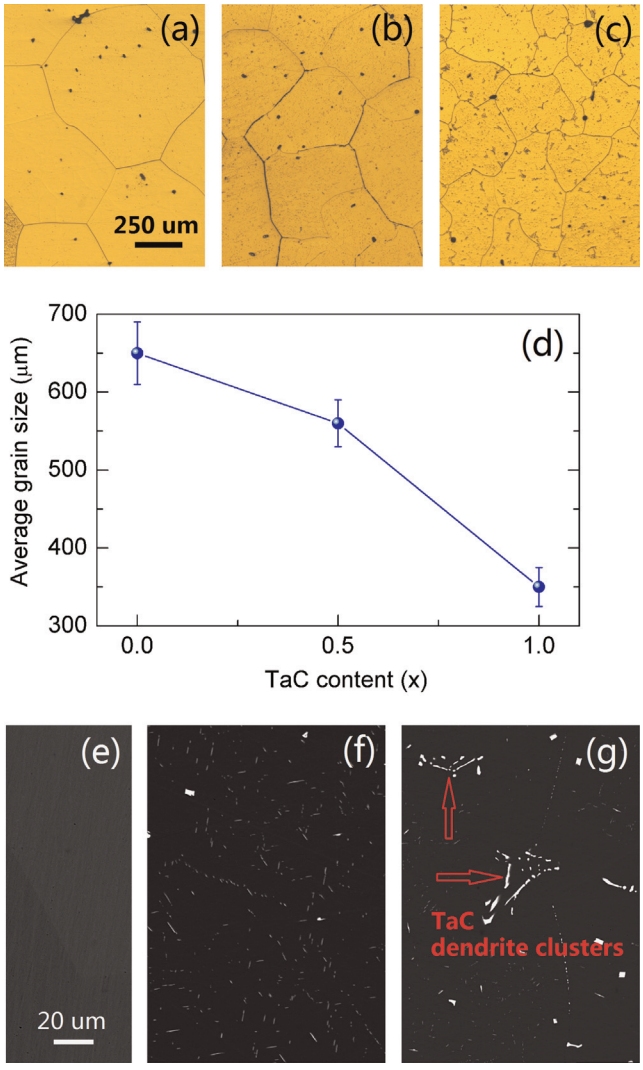

Fig. 2. Optical micrographs of alloys with $x=0$ (a), 0.5 (b) and 1.0 (c). TaC content dependence of average grain size (d). BSE micrographs of alloys with $x=0$ (e), 0.5 (f) and 1.0 (g). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

difficult to accurately detect the C element by EDS). Combining with the existence of TaC phase from XRD analysis (Fig. 1), these bright particles are considered as TaC phase. With a size of $2 \times 10\ \mu m^2$, one can see that these rod-shaped particles are different from the spherical particles of the starting TaC powder. More importantly, large numbers of TaC particles locate within the grain matrix. These features indicate that the starting TaC powders decompose during the electric arc melting and, Ta and/or C atoms partly enter into the Fe–Ga alloy matrix during the solidification. During the subsequent heat treatments, the TaC phase precipitates again and grows up in the grain matrix. For the alloy with $x=1.0$ (Fig. 2g), similar TaC particles are also observed within the grain matrix. At the same time, dendrite-like TaC clusters with about 50 μm in size can be produced and aggregated at the grain boundaries (red arrows), which were confirmed by EDS (not shown) and XRD analysis (Fig. 1). Therefore, an *in situ* formation of dual-reinforcement $(TaC_{particle}+TaC_{dendrite})/Fe_{81}Ga_{19}$ composite alloy is obtained in the alloy with $x=1.0$, which is similar to the case of $(TiC_{particle}+TiB_{wisker})/Ti$ composites [19,20].

It is important to correlate the grain refinement behavior and the TaC phase distribution in these studied alloys. During the solidification, the cubic TaC phase nucleates in the high-temperature melt as a primary, high-melting phase. These highly dispersed phase