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Textured, dense and giant magnetostrictive alloy from fissile polycrystal

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ABSTRACT

Textured materials usually promise an enhanced physical effect along their preferred orientation. However, how to orientate the material, especially from a fissile alloy, is still a great challenge. The transition-metal-based alloy, MnCoSi, is a potential low-cost magnetostrictive material, which application is limited by the poor mechanical property and reduced magnetostriction in polycrystal. Here, we demonstrate that, through the approach of high magnetic field solidification with a slow cooling rate, some textured and dense $MnCoSi_{1-x}$ alloys are obtained, which exhibit giant magnetostriction and enhanced manufacturing performance. Meanwhile, by introducing vacancies of Si element, the metamagnetic transition of MnCoSi alloy is adjusted, giving rise to the room-temperature and reversible magnetostriction under reduced driving magnetic field, which is of significance for the practical applications.

1. Introduction

Crystalline materials are usually anisotropic in their properties and the texture plays a key role in determining their application performance. For example, the transport critical current density of superconductors, such as $YBa_2Cu_3O_{7-x}$, is found to depend critically on the degree of texturing in the material [1]; The grain-oriented silicon iron is reported to exhibit the softest magnetic behavior and minimum magnetization losses [2]; As for Bi_2Te_3, its thermoelectric performance is superior in the direction perpendicular to c axis [3]; While in $TbMnO_3$ and $Tb_5Si_{2.2}Ge_{1.8}$, the orientation of these compounds also affects their magnetocaloric effects [4,5]. Therefore, it is very meaningful to impose a preferred orientation on a material, which has an ability to increase its potential in application. Another important application of orientation is in the magnetostrictive materials, which have drawn ever-increasing attention due to their wide applications in acoustic transducers, actuators, stress sensors and so on [6–9]. Actually, enhanced magnetostriction has been found in some textured alloys, such as Fe–Ga [10–13], Terfenol-D [14,15], Ni–Mn–Ga [16,17], and Ni–Mn–In [18,19]. However, there are still some drawbacks in current magnetostrictive materials, such as high-cost (Terfenol-D), limited magnetostriction value (Fe–Ga), or irreversibility (Ni–Mn–Ga and Ni–Mn–In), which have hindered their application to a large extent. So the low-cost magnetic materials with large and reversible magnetostriction are greatly desirable.

Recently, a transition-metal-based alloy, MnCoSi, has attracted more and more interest due to its special magnetic structure and interesting magnetic effects [20–24]. It exhibits a double helical magnetic structure with magnetic Mn and Co moments rotating about their respective axes [20–24]. With the application of a magnetic field higher than 2.5 T at room temperature, MnCoSi undergoes a metamagnetic transition from nonlinear antiferromagnetic (AFM) phase to high magnetization (HM) phase, leading to large magnetocaloric and magnetoresistance effects [20–25]. Besides, this phase transition is accompanied with considerable changes in lattice parameters, suggesting that MnCoSi alloy would be a promising magnetostrictive material [26–28]. It is reported that the volume change in polycrystalline MnCoSi alloy at 300 K is about −0.2% [27] and the corresponding length change is estimated to be about 667 ppm, which is far below the

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magnetostriction value of its orientated pieces [26,27]. This result implies that the magnetostriction of polycrystalline MnCoSi bulk can be further improved in a textured sample. On the other hand, as a common feature of the magnetic-phase-transition materials [29], MnCoSi is very fissile. During the cooling process of cast ingot, this alloy undergoes a structural transformation from Ni_2In to TiNiSi phases at 1190 K [27]. The stress generated from the phase transition is high enough to break the sample [30] and cracks would form in the ingot, leading to the poor mechanical property of MnCoSi alloy. Therefore, besides obtaining a textured sample, it is still a challenge to improve the manufacturing performance of this magnetic functional alloy.

For gaining textured MnCoSi alloy, there are some alternative proposals. Magnetic annealing is a conventional method to orientate ferromagnetic materials, but the sintering process must be carried out below their Curie temperature. For MnCoSi alloy, the magnetic ordering temperature is around 380 K [27], which is not high enough for the magnetic annealing. Another effective method is directional solidification [31]. However, according to our experimental result, it is difficult to perform this technology on MnCoSi alloy owing to the giant volume change during the cooling process [30,32]. As for the improvement of mechanical properties, a more dense MnCoSi bulk can be obtained with a slow solidification rate due to the gradual release of stress during the cooling process [27]. Unfortunately, no preferred orientation is observed in this dense alloy. Thus orientation and high densification extent seem to be contradictory in MnCoSi alloy.

High-magnetic-field solidification with a slow cooling rate is a promising method to solve these two problems in MnCoSi alloy. In order to obtain textured and dense sample by this means, three prerequisites should be met: the first is the thermal-treatment temperature is high enough to partially melt the alloy, because this semi-solid state is helpful to orientate the crystalline grain [33,34]; the second is, at that high temperature, the anisotropy energy in the paramagnetic state (because the sintering temperature is usually higher than magnetic ordering temperature) is strong enough to exceed the energy associated with thermal disordering effects, which can induce the alignment of particle in a high magnetic field [33]. And the last is a slow enough cooling rate, which is beneficial for the release of stress generated from the structural transformation. Based on the aforementioned criteria, some dense and textured Si-vacant $MnCoSi_{1-x}$ ($x = 0$, 0.01, and 0.02) bulks are prepared by this method. Here the purpose of introducing vacancies of Si element is to adjust the metamagnetic transition of MnCoSi, which will be discussed later.

2. Experiment

Polycrystalline $MnCoSi_{1-x}$ ($x = 0$, 0.01, and 0.02) alloys were prepared by arc-melting the appropriate amounts of raw materials in a water-cooled copper crucible under a high-purity argon atmosphere for three times. Then the ingots were sealed in vacuumed quartz tubes. In order to prevent the break of the tubes caused by structural transformation (at 1190 K [27]) during the solidification, the quartz tube was sealed in another quartz tube with bigger diameter in high vacuum atmosphere. Theses bilayer tubes were heated at 1500 K for 30 min and then slowly cooled down to 1123 K with a rate of 2 K/min under a high magnetic field of 6 T. After that, the applying field was removed and the samples were cooled down to room temperature. Finally, the prepared samples were further annealed at 1123 K for 60 h and slow cooled to room temperature in 72 h under vacuum environment.

Crystal structures of $MnCoSi_{1-x}$ ($x = 0$, 0.01, and 0.02) alloys were identified by XRD at room temperature. Magnetic measurements were performed on a superconducting quantum interference device (SQUID, Quantum Design) magnetometer. Magnetostriction measurement was carried out using a standard strain-gauge technique on a physical property measurement system (PPMS, Quantum Design). The surface of the samples was investigated by a scanning electron microscope (SEM). Compression-strain measurement was performed on a universal material testing machine.

3. Results

3.1. Characterization of the samples

To characterize the preferred orientation of high-magnetic-field treated alloys, a transverse section of the sample with the direction perpendicular to the magnetic field is cut for X-ray diffraction (XRD) measurement. For comparison, the XRD pattern for the polycrystalline powder is also presented. As shown in Fig. 1, the powder sample displays a random crystallographic orientation and all the peaks can be indexed as a TiNiSi structure. In the case of textured alloy, many diffraction peaks are remarkably suppressed and only one greatly enhanced (1 1 1) peak can be observed, indicating that the sample is orientated by a high-magnetic-field solidification approach. In order to verify the effect of high magnetic field on the formation of texture in MnCoSi alloy, a reference MnCoSi sample is prepared under zero magnetic field using the same annealing and cooling conditions as that in high-magnetic-field solidification. The XRD pattern of the reference sample is similar to that of the powder sample, which is also shown in Fig. 1. This result suggests that the texture cannot be formed without the magnetic field during the slow-cooling-rate solidification due to the weak temperature gradient caused by low cooling rate (2 K/min). Moreover, the (1 1 1) peak shifts to the right with the introduction of vacancies of Si element, suggesting the lattice distortion in these Si-vacant alloys.

3.2. Morphology and manufacturing property of the samples

The micromorphology of the textured MnCoSi alloy is studied by scanning electron microscope (SEM). For comparison, the alloy prepared by induction melting method is also investigated. Fig. 2a shows the SEM image of surface for as-cast alloy. Due to the giant strain caused by volume change during the rapid cooling, this alloy is full of cracks. As shown in the inset of Fig. 2a, the as-cast sample

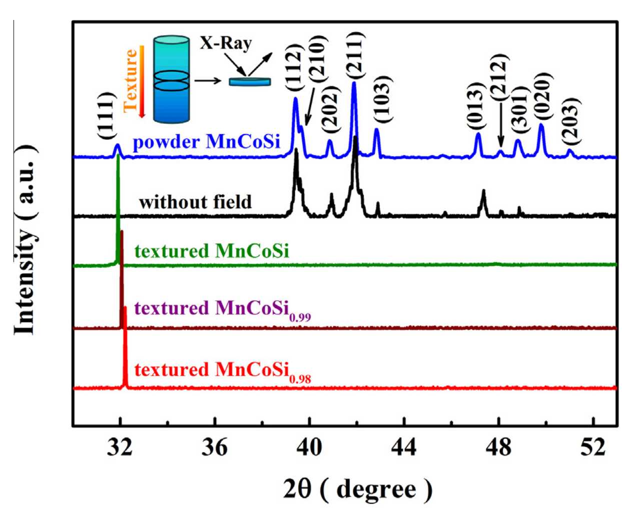

Fig. 1. XRD patterns for powder MnCoSi, reference MnCoSi and textured $MnCoSi_{1-x}$ ($x = 0$, 0.01, and 0.02) alloys. The inset is the schematic illustration of X-ray measurement.