Materials Science & Engineering A 626 (2015) 474–479

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

A macroscopic constitutive model of temperature-induced phase transition of polycrystalline Ni_2MnGa by directional solidification

Yuping Zhu*, Yunling Gu, Hongguang Liu

Institute of Mechanics and Engineering, Jiangsu University, Zhenjiang 212013, China

ARTICLE INFO

Article history:
Received 14 November 2014
Received in revised form
23 December 2014
Accepted 24 December 2014
Available online 6 January 2015

Keywords:
Ferromagnetic shape memory alloy
Directional solidification
Constitutive model
Temperature
Strain

ABSTRACT

Directional solidification technology has been widely used to improve the properties of polycrystalline Ni_2MnGa materials. Mechanical training can adjust the internal organizational structures of the materials, reduce the stress of twin boundaries motion, and then result in larger strain at lower outfield levels. In this paper, we test the microscopic structure of Ni_2MnGa polycrystalline ferromagnetic shape memory alloy produced by directional solidification and compress it along two axes successively for mechanical training. The influences of pre-compressive stresses on the temperature-induced strains are analyzed. The macroscopic mechanical behaviors show anisotropy. According to the generating mechanism of the macroscopic strain, a three-dimensional constitutive model is established. Based on thermodynamic method, the kinetic equations of the martensitic transformation and inverse transformation are presented considering the driving force and energy dissipation. The prediction curves of temperature-induce strains along two different directions are investigated. And the results coincide well with the experiment data. It well explains the macroscopic anisotropy mechanical behaviors and fits for using in engineering.

1. Introduction

Ferromagnetic shape memory alloy (FSMA) is found as a kind of new smart materials in the last decade. With large output strain, high response frequency and other integrated features, FSMA has already become the research focus in the field of smart materials. Ni_2MnGa is the most commonly investigated ferromagnetic shape memory alloy, which has both ferromagnetic and thermoelastic martensite transformation characteristics. Its phase transformation behaviors can be induced by temperature, stress or magnetic field. The single crystal Ni_2MnGa has been investigated roundly in most aspects, such as crystal structure, phase transition characteristics, deformation mechanism, and hysteresis characteristics etc [1–5]. Due to the complexity of preparation process in single crystal Ni_2MnGa, it is hard to be put into mass production. Furthermore, high cost, heavy brittleness and low strength also constrain the practical application of this material in engineering [6].

In order to overcome these problems, many researchers proposed Ni_2MnGa particle reinforced composite materials, magnetic shape memory alloy thin films, polycrystalline ferromagnetic shape memory alloys, adding trace elements and other methods [7–13] to improve the mechanical properties and magnetic shape memory effect, and promote its application in practical engineering problems. In general, the martensitic transformation in polycrystalline Ni_2MnGa produces a microstructure with self-accommodated multi-variants, and the distribution of its grains may locate in any directions. So the polycrystalline Ni_2MnGa can not produce large magnetic-induced strain. However, polycrystalline Ni_2MnGa prepared by directional solidification method or the magnetic field heat treatment can help the material obtain a strong texture, making its grains close to the preferential orientation. It may enhance the magnetocrystalline anisotropy and magnetic-induced strain [14]. In addition, polycrystal with initial texture have the quality of simple preparation, low cost and high compressive strength. So, polycrystalline Ni_2MnGa with initial texture has a very broad application prospect.

It is shown that the directional solidification method to obtain texture in polycrystalline Ni_2MnGa is mature and effective [15–20]. The directional solidification method can obtain fiber texture in polycrystalline Ni_2MnGa. Mechanical training, namely successively compressing the samples along two axes or three axes, can adjust the internal organizational structure of the samples orderly, which may reduce the twinning stress and promote the martensite twin boundary motion under an external force or magnetic field. As a result, the strain of the material is promoted. It has been shown

* Corresponding author. Tel.: +86 511 88780197.
E-mail address: zhuyuping@126.com (Y. Zhu).

http://dx.doi.org/10.1016/j.msea.2014.12.108
0921-5093/

that the stress–strain curve of polycrystalline Ni_2MnGa is close to that of single crystal Ni_2MnGa after several times training, and the free recovery strain induced by magnetic field can reach 0.16% [18]. 1% magnetostrictive strain can be achieved at 40 °C, and 0.3% magnetostrain at room temperature [16]. People have also studied the magnetic-induced strains in different directions [18,19], stress–strain curves [15,17] and the effects of solidification direction on temperature-induced strain [21–24] of the directional solidification polycrystalline Ni_2MnGa after training. Mechanical training is essential for reducing the stress of twin boundaries motion and increasing strain.

The directional solidification technology has been widely used to improve the properties of the materials and theoretical researches of them have been conducted in depth. Yaguchi et al. [25] investigated the elastic properties of directionally solidified polycrystal through self-consistent approach, and predicted elastic stiffnesses numerically of a Ni-base directional solidification alloy. Sai et al. [26] proposed micro- mechanically based constitutive models to study inelastic behavior of directionally solidified materials. Yaguchi [27] developed an anisotropic constitutive model of a Ni-based directionally solidified superalloy, and made a comparison with experimental data. Martin et al. [28] proposed a mean field mechanical model describing the inelastic behavior and strong anisotropy of directionally solidified materials. The above models have considered microstructures of directionally solidified materials during developing constitutive models. Even though this class of model was based on a close investigation of the physics of the material and thus provided valuable insight on the phase transformation at the crystalline and grain levels, it does possess disadvantages such as the numerous numerical computations and the complexity of the micro-to-macro transition.

Many macroscopic models of traditional shape memory alloy were proposed [29–33]. Based on the thermodynamical approach, thermo-mechanically-coupled constitutive models were developed to study mechanical behaviors and exploit its potential features, promoted its wide application in engineering.

Although directionally solidified polycrystalline FSMA possesses unique mechanical properties, it also has the similar features with Ni-based materials. Thus the macroscopic and microscopic methods to analyze Ni-based materials are worth to be used for reference. As a consequence, an increasing interest in the use of FSMA in innovative engineering applications makes it necessary to develop more accurate constitutive models describing the complex material responses.

In this paper, we will train the directional solidification polycrystalline Ni_2MnGa through compressing the samples successively along two axes, and then test their mechanical properties to acquire various mechanical performance parameters under the coupling action of stress and temperature. According to the generating mechanism of the macroscopic strain, a three-dimensional constitutive model is established considering material anisotropy. Fewer material constants which are used to determine model parameters are needed, which makes it easy to use and enable quick computations. And that provides theoretical guidance for the application of the material in the engineering.

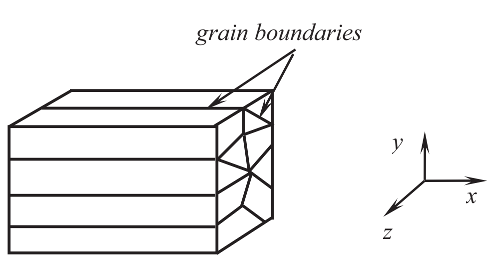

Fig. 1. Schematic view of directionally solidified FSMA.

2. Experimental

The materials are bought from Beijing University of Aeronautics and Astronautics. Ingots are prepared by vacuum arc melting with pure elements (Ni 99.95, Mn 99.95, Ga 99.95). The raw material surface is polished firstly. In order to obtain uniform material, every furnace charge should overturn 3–4 times. After remelting, the ingots are cast in a hot ceramic mold mounted on a cooling copper plate in order to achieve directional solidification. The alloys are annealed for 48 h at 1000 °C under Ar/5% H_2 atmosphere for homogenization. In order to eliminate internal stress, the alloy is annealed for 1 h at 600 °C.

By the energy spectrum analysis (EDS), the chemical composition of the material is $Ni_{47.07}Mn_{26.13}Ga_{26.80}$at.%. At room temperature, the material is in the martensite phase. The crystalline structure of the sample is measured by multi-function X-rad diffraction interferometer that shows 5 M martensite at room temperature. After solidifying strain gauges under high temperature, the DSC curve shows phase transformation temperature: M_s=56 °C, M_f=50 °C, A_s =110 °C, A_f=120 °C and Curie temperature T_C=150 °C.

The rectangular sample is seen in Fig. 1, which the longest dimension is parallel to directional solidification. The dimensions of sample are $15.0 \times 6.0 \times 10.1$ mm^3.

Fig. 2(a) and (b) are the optical figures of microscopic structure of the original sample which are observed by KEYENCE VHX-1000 microscope. Grinding the directional solidification surface and cross section of the sample from coarse to fine with metallographic sandpaper 200, 400, 600, 800, 1200. In order to make the surface smooth, the sample is polished by the polisher. The directional solidification surface and cross section of the sample is corroded in the uniform mixing reagent with 2.5 g $FeCl_3$, 7.5 ml HNO_3 and 50 ml ethyl alcohol. During this process, we observe the

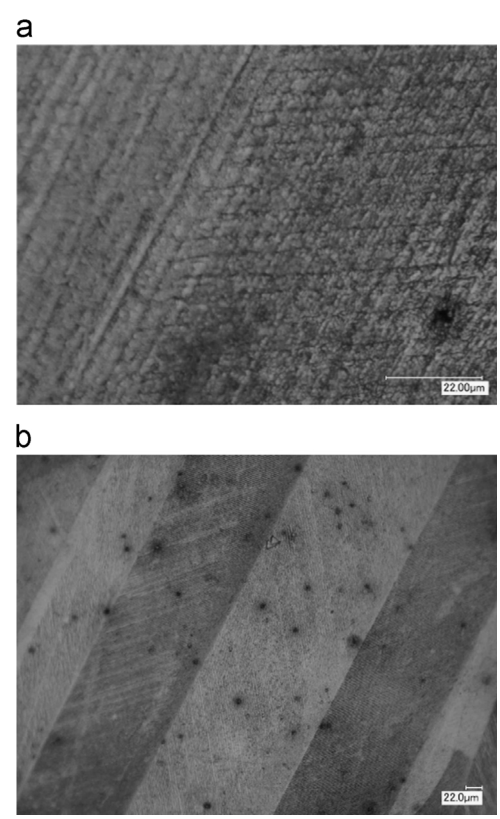

Fig. 2. The optical figures of microscopic structure of $Ni_{47.07}Mn_{26.13}Ga_{26.80}$at%. (a). The directional solidification direction and (b). The direction perpendicular to directional solidification.