Scripta Materialia 134 (2017) 85–90

Contents lists available at ScienceDirect

Scripta Materialia

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

Regular Article

Detwinning of hierarchically structured martensitic variants in a directionally solidified non-modulated Ni-Mn-Ga alloy under uniaxial loading

Long Hou [a], Yanchao Dai [a], Yves Fautrelle [b], Zongbin Li [c], Zhongming Ren [a], Claude Esling [d], Xi Li [a,b,*]

[a] State Key Laboratory of Advanced Special Steels, Shanghai University, Shanghai 200072, P.R. China
[b] EPM-Madylam, ENSHMG, BP 38402 St Martin d'Heres Cedex, France
[c] Key Laboratory for Anisotropy and Texture of Materials, Northeastern University, Shenyang 110819, P.R. China
[d] Laboratoire d'Étude des Microstructures et de Mécanique des Matériaux (LEM3), CNRS UMR 7239, Université de Lorraine, 57045 Metz, France

ARTICLE INFO

Article history:
Received 6 January 2017
Received in revised form 21 February 2017
Accepted 26 February 2017
Available online 21 March 2017

Keywords:
Magnetic shape memory alloys (MSMAs)
Ni-Mn-Ga
Compression
Electron backscatter diffraction (EBSD)
Detwinning

ABSTRACT

The detwinning evolution of hierarchically structured martensitic variants in a directionally solidified non-modulated Ni-Mn-Ga alloy has been investigated by applying uniaxial compression parallel to the parent $[001]_A$ orientation with a cumulative strain of 3%, 7.3% and 10%, respectively. After each compression, the crystallographic orientations are obtained by manually indexing the Kikuchi patterns and the corresponding twinning relationships between the variants are also calculated. The results indicate that for both the intra-plate major-minor variants and inter-plate major-major variants, the detwinning occurs on the twins with high Schmid factor, resulting in a martensite only composed of favorable variants with $[110]_{NM}$ orientation parallel to the compression direction.

Ferromagnetic Ni-Mn-Ga alloys have attracted much attention due to the excellent magnetic shape memory effect (MSME), being conceived as promising sensor and actuator materials [1–4]. The large magnetic-field-induced strain (MFIS) can be attainable through field-induced twin boundary motion [2,5–7]. The large MFIS, almost equal to the theoretical maximal value, has been achieved in the modulated martensite (e.g. 6% in 5 M martensite and 10% in 7 M martensite) [2, 8]. In general, non-modulated (NM) Ni-Mn-Ga alloy is thought to be impossible to exhibit large MFIS, due to high twinning stress [9], although its theoretical maximal value is up to ~20% [10]. Recently, through effective magneto-mechanical training [11] or alloying with other elements (i.e., Co and Cu) [12], an obvious MFIS can be obtained in the NM Ni-Mn-Ga alloys. However, the untrained, self-accommodated NM martensite is composed of a hierarchically twinned microstructure, where higher-order, smaller twins form within lower-order twins [13–15]. The martensitic plates are composed of alternately distributed thick and thin nano-lamellae, labeled as major and minor variants [16]. It has been determined that there exist two typical martensite variant groups, composed of parallel plates with straight edges and non-parallel plates with bent edges, denoted as Group I and Group II for easy depiction. An important pre-requirement for giant MFIS to occur is to simplify the self-accommodated martensite structure [17,18]. This process, termed training, is usually done by uniaxial compression tests along the ⟨001⟩ crystallographic directions referred to the high temperature austenite phase in a proper sequence. Nowadays, the training process of as-grown Ni–Mn–Ga single crystals is done frequently and has been analyzed to some extent [13,19,20]. Particularly, the detwinning evolution of NM Ni-Mn-Ga thin film under tensile stress has been successfully observed by in situ transmission electron microscopy (TEM) [21–23]. However, the exact information about the detwinning evolution of the hierarchical twin microstructure under compression, especially with respect to the compression direction, is lacking. Moreover, during the detwinning process, the twin relationships between variants pairs are also quite necessary. To understand the underlying detwinning mechanism in the hierarchically structured NM martensite, systematic crystallographic characterization and corresponding twinning relationships of the martensitic twins are investigated. In this paper, using mostly the electron backscatter diffraction (EBSD) technique the detwinning process of a NM martensite during the consequent uniaxial compression is shown and analyzed in detail. It is shown that the detwinning occurs on the twins with high Schmid factor for both the intra-plate major-minor variants and inter-plate major-major variants, resulting in a martensite only composed of favorable variants with $[110]_{NM}$ orientation aligned to the compression

* Corresponding author at: State Key Laboratory of Advanced Special Steels, Shanghai University, Shanghai 200072, P.R. China.
E-mail address: lx_net@sina.com (X. Li).

http://dx.doi.org/10.1016/j.scriptamat.2017.02.045
1359-6462/

direction. The present research would bring about not only a comprehensive understanding to the martensitic variant detwinning in hierarchical structure but also a guideline for martensite training.

Single crystalline Ni-Mn-Ga alloys with the nominal composition of $Ni_{54}Mn_{24}Ga_{22}$ (at%) were prepared by arc-melting under argon atmosphere. The alloys were remelted four times and then suctioned into a quartz tube to obtain a cylinder shaped alloy with 3 mm in diameter and 150 mm in length. The cylinder shaped alloy was then enveloped in a high-purity corundum tube with an inner diameter of 3 mm and length of 200 mm for directional solidification. The samples were prepared by directional solidification through a Bridgman-Stockbarger-type furnace equipped with a pulling system and temperature controlling units. During the experiments the samples in the corundum crucibles were remelted and directionally solidified by pulling the crucible assembly into the liquid metal (Ga-In-Sn alloy) cylinder. Then the as-solidified alloy was homogenized at 1173 K for 24 h in a sealed vacuum quartz tube, followed by the water quenching. The section in stable growth zone with size of 3 mm in diameter and 5 mm in length was

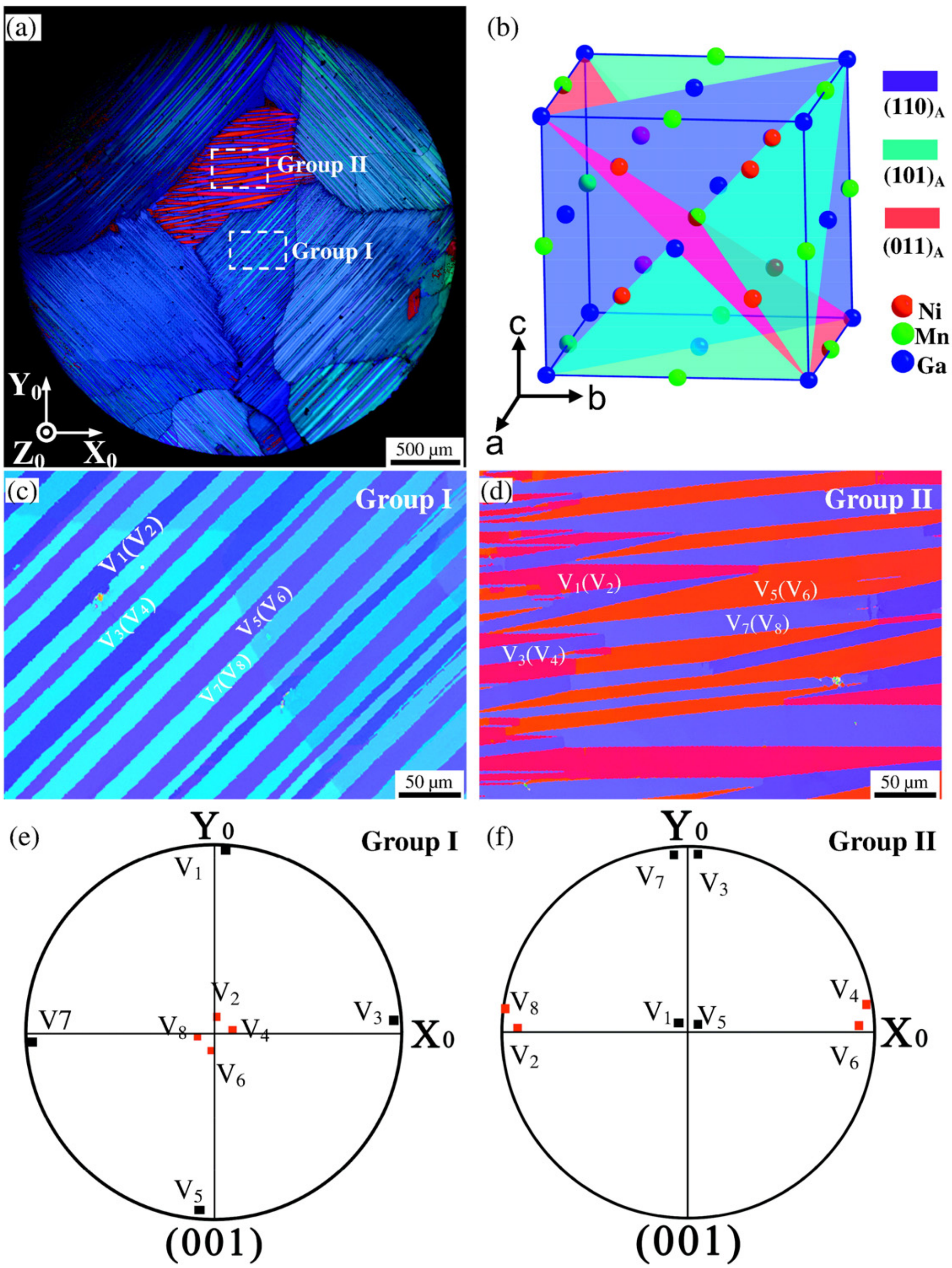

Fig. 1. (a) EBSD maps (IPF mode) of a directionally solidified non-modulated Ni-Mn-Ga alloy concluding two typical martensitic variants groups (defined as Group I and II); (b) Schematic model of the possible twinning plane according to the simplified Bain model shown in the austenite cell; (c) and (d) the magnified orientation images corresponding to Group I and II; (e) and (f) the $(001)_{NM}$ pole figures corresponding to Group I and II. Note that Euler angles of major variant (black) and minor variant (Red) in each martensite plate are measured from corresponding overlaying Kikuchi patterns.