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Detwinning process of martensite in $Ni_{58}Mn_{25}Ga_{17}$ as a high temperature shape memory alloy under uniaxial compression

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

[a] State Key Laboratory of Advanced Special Steels, Shanghai University, Shanghai, 200072, PR 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, PR China
[d] Laboratoire d'Étude des Microstructures et de Mécanique des Matériaux (LEM3), CNRS UMR 7239, Université de Lorraine, 57045, Metz, France

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ABSTRACT

The Ni-rich Ni-Mn-Ga alloy as a high temperature shape memory alloy has been directionally solidified, which is consisted of non-modulated (NM) martensite with preferred orientation and γ precipitate with a three dimensional net structure. The detwinning process of $Ni_{58}Mn_{25}Ga_{17}$ alloy was investigated under step-wise uniaxial compression with a cumulative strain of 2.5%, 5.5%, 12.9% and 30.2%, respectively. It has been captured how the hierarchically structured martensite variants reorient and the effect of the surrounding γ phase on detwinning process with the increase of compression strain. It can be found that the volume fraction of the original minor lamella gradually increases and then it occupies the whole plate. The detwinning of new microtwins is not observed during further compression. The results indicate that the move of the intra-plate boundaries is attributed to a higher Schmid factor of the nanotwins. The mobility of the new inter-plate boundary is mainly dependent on the preferred orientation of the lamella inside martensite variants. The present study provides useful insights for microstructure training in high temperature shape memory alloys including martensite and γ phase.

1. Introduction

Shape memory alloys (SMAs) are a class of smart materials capable of undergoing a reversible solid-to-solid phase transformation via thermal, mechanical or magnetic field which may result in large recoverable inelastic strains (Lagoudas et al., 2012; Lester et al., 2015; Morin et al., 2011). Ni-Ti alloys as a typical representation of SMAs can be induced by thermal field to obtain a large recoverable strains of 1–8% (Kato et al., 2017; Manchiraju and Anderson, 2010; Manchiraju et al., 2011; Zhang et al., 2016). Moreover, magnetic shape memory alloys (MSMAs) exhibit not only conventional temperature- or stress-activated shape memory behavior but also high response to magnetic field. Application of a magnetic field results in twin boundary motion and martensite variant reorientation, with a change in the shape and dimensions of the material. Magnetic field-induced strains (MFIS) is based on the rearrangement of crystallographic domains to reduce the Zeeman energy. Due to the magnetic anisotropy of the martensitic phase, twin variants grow whose easy magnetization axis is aligned with the applied magnetic field. MSMAs with giant MFIS in the martensitic phase were widely investigated, e.g. Ni-Mn-X (X = Ga, In, Sn) (Chernenko et al., 2016; Czaja et al., 2016; Huang et al., 2013), Co-Ni-Al (Bartova et al., 2008), Ni-Fe-Ga (Chernenko et al., 2009) and Fe-Pd (Bischoff et al., 2016; Kato et al., 2002). Ni-

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

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Mn-Ga alloys have received a widespread attention as a kind of promising materials due to the maximum MFIS of 12% being found in NM tetragonal crystal structure (Sozinov et al., 2013). For Ni-Mn-Ga shape memory alloys, composition variation has significant influences not only on the martensitic transformation temperature, but also on the phases classification, resulting in a sequence of changes about structures and properties (Dai et al., 2017a,b; Huang et al., 2013). Ternary phase diagram of Ni-Mn-Ga alloy has revealed austenite phase (β phase) and precipitate (γ phase) formed at specific composition range (Santamarta et al., 2010). The γ phase is a solid solution with more Ni and less Ga than β phase. The Ni-Mn-Ga alloys with γ phase possess a high martensitic transformation temperature (up to 350 °C), showing their potentials as high temperature shape memory alloys (HTSMAs) (Cesari et al., 2008; Ma et al., 2007; Nespoli et al., 2017). Moreover, γ phase has significant effects on the shape memory effects and the mechanical properties. With regard to β phase, the phase transformation would take place when the temperature drops to a certain point and then it changes into different martensitic structures. During the martensitic transformation, a progress of self-accommodation results in a specific distribution of variants, which allows to minimize the elastic energy consumption (Chulist et al., 2016).

The austenite phase with preferred orientation is usually directionally solidified by a seedless Bridgman method (Tian et al., 2010; Zheng et al., 2015). However, the orientations of multiple related martensite variants are complicated and difficult to control. Usually, by applying a mechanical training containing a series of compression along one or two axes, the volume fraction of particular martensite variant will change along with the motion of twin boundaries. As a result, a single or two-variant state is achieved (Chulist et al., 2013; Szczerba and Chulist, 2015). Twin boundary motion is the mechanism responsible for the mechanically induced deformation. A lot of investigations involved in plasticity deformation and twin boundary motion in Mg alloys have been reported under different training programs (Cui et al., 2017; Dong et al., 2017; Khan et al., 2011; Kim et al., 2017; Lou et al., 2007). Some analogous mechanical trainings were applied on Ni-Mn-Ga alloy in order to afford some plastic accommodation (Szczerba et al., 2014). At present, an extensive investigations regarding to stress-induced detwinning in Ni-Mn-Ga alloys have been conducted mainly on reducing the twin stress by mechanical training. Among them a few reports record the evolution of microstructures and orientations during compression process (Chulist et al., 2010; Szczerba and Chulist, 2015; Szczerba et al., 2014; Zou et al., 2017). In our previous study, a pure non-modulated (NM) martensite and a two-phase structure consisted of austenite and NM martensite at ambient temperature have been researched under a step-wise uniaxial compression by electron backscatter diffraction (EBSD) tracing (Dai et al., 2017a,b; Hou et al., 2017). However, the Ni-rich Ni-Mn-Ga alloys as HTSMAs have never been discussed by the method of EBSD measurement after each strain. It is not known how the martensite variants reorient and the effect of the surrounding γ phase on detwinning process with the increase of compression strain in Ni-rich Ni-Mn-Ga alloys. The present study has been carried out to address these issues, which will provide significant information for the development of the alloys as HTSMAs. In addition, the γ phase with three dimensional net structure strengthens the ductility of the HTSMAs and make it possible to be the framework of material. The study of detwinning in a single variant group is helpful to clarify the complicated evolution mechanism of hierarchically structured martensite variants and the effect of the surrounding γ phase. It is helpful to design and filtrate favored orientation initial sample to improve practical properties.

In this paper, the special structure consisting of martensite with preferred orientation and γ precipitate with a three dimensional net structure was directionally solidified. The direct evidence on the detwinning process induced by stress was captured in $Ni_{58}Mn_{25}Ga_{17}$ alloy measured by EBSD and transmission electron microscopy (TEM). The similarities and differences of evolution mechanism were discussed on the hierarchically structured martensitic variants. The present research provides instructive guidance for the reorientation of complicated multi-variants under uniaxial compression.

2. Experimental details

Ni-Mn-Ga alloy with nominal composition of $Ni_{58}Mn_{25}Ga_{17}$ was directionally solidified at a growth speed of 5 μm/s. The raw ingots with high-purity Ni (99.99 wt%), Mn (99.9 wt%) and Ga (99.99 wt%) were melted in an arc-melting furnace under argon atmosphere. The ingots were re-melted five times for homogeneity and suctioned into a quartz tube to cast specimen. A thin rod with diameter of 3 mm and length of 120 mm was obtained and then enveloped in a tube of high-purity corundum for directional solidification.

The column sample with a diameter of 3 mm and a length of 6 mm was cut from the stable growth zone of directionally solidified rod. The compression process was performed with MTS809 material testing system. Uniaxial compression tests were conducted along the direction of directional solidification with a constant speed of 0.15 mm/min at room temperature. The cross section at different strain stages was measured by EBSD method in order to characterize martensite variants reorientation and detwinning process. In order to remove the residual stress surface layer, an electrolytic etching with a solution of 20% vol% HNO_3 in CH_3OH was used at 12 V for 25 s at ambient temperature. The sample after each compression needed to re-polish in order to obtain high indexing rate. The microstructures were examined using scanning electron microscopy (Hitachi SU70 and FEI Quanta 450). The crystal orientations of constituent phases and configurations of martensite variants were characterized by a Hikari high speed electron backscatter diffraction (EBSD) camera. All EBSD data were analyzed by OIM analysis software (EDAX, USA). The cross section and the detail maps were detected with a step size of 3 μm and 0.8 μm, respectively. Grain CI standardization and Grain dilation were selected to clear up the noise. The data with high confidence index (CI) value (CI > 0.2) were selected. Notably, every NM martensite plate contains two alternately distributed fine lamellae. The two fine NM martensite lamellae are of different thicknesses and the thinner one with a width of hundreds of nanometers is too fine and beyond the resolution of the present automated EBSD analysis system. That means the individual NM martensite plate is identified only by the orientation of the thicker lamella. Even though, the thinner lamella still can be recognized by manually indexing Kikuchi pattern, as discussed in our previous reports (Hou et al., 2017). The