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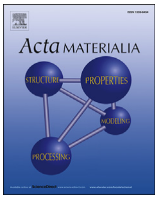

Full length article

Effects of surface modifications on the fatigue life of unconstrained Ni-Mn-Ga single crystals in a rotating magnetic field

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A B S T R A C T

Long-term fatigue life during high-cycle magnetic-mechanical actuation is crucial to the application of Ni-Mn-Ga ferromagnetic shape memory alloys (FSMAs). It has been reported that long fatigue life can be achieved by both reducing surface damage and constraining Ni-Mn-Ga single crystals to exhibit much lower strain than the theoretical limit. In the present study, the fatigue life of Ni-Mn-Ga single crystal samples treated with various surface modifications was investigated in a rotary fatigue testing instrument. The apparatus minimally constrained the samples and allowed for magnetic-field-induced strain (MFIS) close to the theoretical limit. We first treated the samples with electropolishing, which we found created more surface defects than those of the mechanically polished sample. These defects acted as dispersed pinning sites for twin boundaries and nucleated cracks easily due to the localized stress concentration, resulting in reduced fatigue life. We then studied the introduction of residual compressive stresses imparted by micropeening. Although micropeening increased surface roughness, it produced a uniform surface morphology and a finely twinned structure. We argue that the large groups of dislocations did not pile up and the stress distribution was more homogeneous due to the fine twin structure, lowering the crack nucleation rate. Consequently, the fatigue life of unconstrained Ni-Mn-Ga single crystals with large MFIS was significantly improved by the micropeening treatment.

1. Introduction

Since the discovery of magnetic field-induced strain (MFIS) in ferromagnetic shape memory alloys (FSMAs) with strain greater than that obtained in magnetostrictive materials, FSMAs have attracted much attention due to their promising application in actuators and sensors [1–4]. At present, off-stoichiometric Ni_2MnGa FSMAs have been studied intensively because they exhibit high MFIS up to 12% due to a large magnetic anisotropy constant and high magnetic and martensitic transformation temperatures [5–8]. On the microscopic scale, the MFIS is caused by the magnetic-field-induced reorientation of the twin variant structure, in which the short axis (c) of the martensite close-to-tetragonal crystal lattice aligns with the magnetic field direction [9–11]. Put another way, the MFIS is a magnetoplastic deformation resulting from twin boundary movement driven by magnetostress [12]. Since the FSMAs are required to undergo long-term cycling of MFIS for practical applications, it is crucial to study the magneto-mechanical fatigue behavior of FSMAs.

The fatigue behavior is closely related to the nucleation of cracks during high-cycle magnetic-mechanical actuation. If the twin boundary motion is obstructed by interacting twins, stresses concentrate at twin boundaries, creating a pile-up of twinning dislocations [13,14]. Thus, cracks nucleate at twin boundaries due to stress concentration and eventually lead to the fracture of FSMAs. Generally, the twin boundaries can move readily in the crystals with thick twins, and large MFIS can be obtained. But cracks also easily nucleate in such crystals, resulting in a short lifetime [15,16]. In contrast, twin boundaries cannot move long distances in a sample consisting of many thin twins, since twin boundary movement is strongly hindered by the densely twinned microstructure. Thus, MFIS is relatively smaller and the stress distribution is more homogeneous than that in a coarse twin

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Table 1
Sample groups with different surface treatments. Each group has five disc samples with ~1.4 mm thickness.

Group	I	II	II_{half}	III	IV
Surface treatment					
First electropolishing (volume ratio of ethanol and nitric acid is 2:1, 12 V, 20 s)	✓	✓	✓	✓	✓
Mechanical polishing (0.04 μm)	✓	✓	✓	✓	✓
Second electropolishing (volume ratio of ethanol and nitric acid is 2:1, 12 V, 20 s)		✓	√(half sample)	✓	✓
One-side micropeening (~100 μm powder, 8 s, nozzle pressure: 25 psi)				✓	✓
Two-side micropeening (~100 μm powder, 8 s, nozzle pressure: 25 psi)					✓

microstructure. Researchers have suggested that crystals with thin twin structure are more resistant to crack nucleation and so exhibit a longer fatigue life [13,17].

On the other hand, it is known that the surface defects could act as dispersed pinning sites which hinder the motion of twin boundaries and cause stress concentrations [18,19]. Therefore, it has been suggested that the twinning stress can be reduced largely by removing the damaged surface layer, which should improve fatigue life considerably [16,20]. Straka et al. demonstrated enhanced fatigue life for samples with a fine twin microstructure, which was stabilized by micropeening the surface [21]. In addition, macroscopic constraints as an unavoidable component of certain sample holders have also been considered as one of the key factors that affect the MFIS as well as fatigue life [13,22,23]. The constraints reduce and even block the movement of twin boundaries, and lead to a remarkable reduction of MFIS [24]. Meanwhile, the fatigue life is shortened in single-domain crystals, because constraints hinder the microstructure from adapting to the internal stress; while a prolonged fatigue life can be achieved in crystals exhibiting self-accommodated multi-domain martensite since the dense twin structure could be stabilized by the constraints [13,25].

Consequently, it is a challenge to develop such a Ni-Mn-Ga FSMA that shows both large MFIS and long fatigue life. In order to achieve this goal, it is desirable to design a crystal in which twins are fine but do not obstruct each other [16]. In the present work, the effects of surface modifications on the fatigue life of unconstrained Ni-Mn-Ga single crystals have been studied in detail. The fatigue life was diminished significantly following an electropolishing treatment, which caused pitting and surface non-uniformity. Notably, micropeening gave rise to a fine twin microstructure, leading to a homogeneous stress distribution. Following micropeening, fatigue life was improved remarkably while the MFIS remained large.

2. Experimental

A single crystal with nominal composition $Ni_{50}Mn_{28}Ga_{22}$ was grown using the Bridgman-Stockbarger technique described in detail in Ref. [26]. The growth direction was parallel to $<100>_{austenite}$, and the size of the initial ingot was 6.3 mm in diameter and 75 mm in length. The crystal structure, orientation, and lattice parameters were determined with X-ray diffraction along the length of single crystal using a Bruker D8 diffractometer with Cu Kα radiation. The composition along the length of crystal was investigated using a Hitachi scanning electron microscopy (SEM) with Energy Dispersive Spectroscopy (EDS, Oxford).

Twenty-five disc samples with ~1.4 mm thickness were cut from the 10 M portion of crystal along the axial direction using a Princeton Scientific precision wire saw and divided into five groups with five samples in each group (Table 1). After cutting, all samples

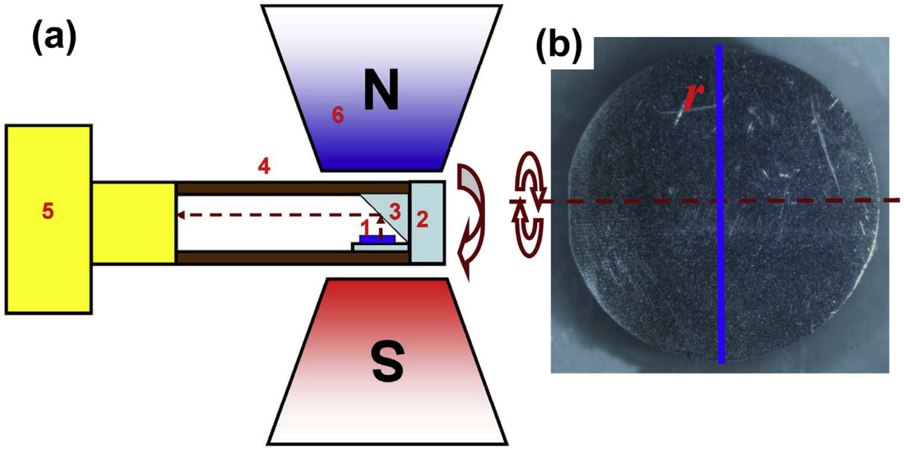

Fig. 1. (A) Schematic of the custom made optical magneto-mechanical device (OMMD) for rotary magnetic-mechanical experiment. The sample (1) was attached to the sample holder (2) by double-sided tape, and then the HD camera (5) recorded the reflection of sample through a mirror (3) while these components were rotated in the magnetic field (6) by a sequence-controlled motor. (b) The image of micropeened IV sample as an example; the dashed line marks the rotation axis and the blue line indicates the diameter which was measured to determine the MFIS; both lines were parallel to <100>. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)