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Experimental investigation on macroscopic domain formation and evolution in polycrystalline NiTi microtubing under mechanical force

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Abstract

This paper reports the experimental results on macroscopic deformation instability and domain morphology evolution during stress-induced austenite → martensite (A → M) phase transformation in superelastic NiTi polycrystalline shape memory alloy microtubes. High-speed data and image acquisition techniques were used to investigate the dynamic and quasi-static events which took place in a displacement-controlled quasi-static tensile loading/unloading process of the tube. These events include dynamic formation, self-merging, topology transition, convoluted front motion and front instability of a macroscopic deformation domain. The reported phenomena brought up several fundamental issues regarding the roles of macroscopic domain wall energy and kinetics as well as their interplay with the bulk strain energy of the tube in the observed morphology instability and pattern evolution under a mechanical force. These issues are believed to be essential elements in the theoretical modeling of macroscopic deformation patterns in polycrystals and need systematic examination in the future.

Keywords: NiTi polycrystal; Superelastic shape memory alloy; Phase transformation; Deformation domain and pattern evolution; Macroscopic domain wall energy

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1. Introduction

Considerable effort and advances, both theoretical and experimental, have been witnessed in the past decades on the investigation of mechanical behaviors of NiTi shape memory alloys. However, in the aspect of deformation instability and the resulted domain pattern evolution of the material during phase transition, for both single crystals and polycrystals, more experimental efforts are clearly needed. Much of the previous experimental research on deformation instability in polycrystalline NiTi during phase transition (see Miyazaki et al., 1981; Leo et al., 1993; Shaw and Kyriakides, 1995, 1997; Brinson et al., 2004 and the references therein) were focused on strip and wire samples under isothermal and/or non-isothermal phase transitions. It is known that the phase transition in NiTi polycrystals is first order in nature and involves intrinsic instability and domain evolution at microscopic level. Thus complicated microstructure interaction and evolution inside the polycrystal are inherent in the transformation process. Under certain conditions, they may even percolate up to the macroscopic level, leading to macroscopic scale domain formation and evolution, as demonstrated through mechanical response and surface morphology. However, exact and detailed observations on pattern evolution in structures like thin walled tubes have not been available in the literature.

Experimental research on deformation instability of NiTi in microtube configuration started only in recent years (Berg, 1997; Li and Sun, 2000, 2002; Sun and Li, 2002). It is motivated by the successful application of microtubes in human implants and surgery instruments. In addition to the facilitation of biaxial loading, the advantage of using the tube configuration is that an isolated high strain domain (martensite phase) can survive in the tube after its nucleation from the austenite matrix and that deformation patterns associated with the domain evolution during the loading process can be produced and observed. The microtubes are usually polycrystalline and nano-grained, with an outer diameter ranging from the smallest of 0.06 to several millimetres and length of a few meters. They are manufactured by cold drawing, therefore the texture of the tubes could be very strong which will give significant anisotropy in both elastic and transformation properties. Previous preliminary study by the authors showed that the transformation process in such a nano-grained polycrystal involves both micro- and macroscopic instabilities and is multi-scale in nature (see Bhattacharye, 2003; Bhattacharye, et al., 2004 and the references therein) and that macroscopic deformation instability under tension manifested itself not only through sharp stress jumps in the nominal stress–strain curves of the tube but also through the various evolving deformation patterns as revealed by careful tube surface observations.

This paper reports some of the key results from the authors' recent experimental investigation on macroscopic domain formation and evolution in the superelastic polycrystalline NiTi microtubing under uniaxial tensile force. The purpose of the research is to obtain quantitative information on the spatiotemporal evolution of the deformation patterns through systematic measurement and eventually to provide critical data for future theoretical development of this type of material. The material properties and test procedures are described in Section 2. Section 3 gives a detailed description of the experimental results. Discussions of the results are given in Section 4 and the conclusions are given in Section 5.