Constrained Phase-Transformation of a TiNi Shape-Memory Alloy

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The phase-transformation behavior of a TiNi shape-memory alloy (SMA) under constraint of a constant strain is experimentally investigated by means of mechanical testing and differential scanning calorimetry (DSC) measurements. It is indicated that the reverse-transformation-temperature span under constraint is much larger than that of the unconstrained state. After an incomplete constrained transformation cycle, a two-stage recovery-stress in the constrained state as well as a two-stage recovery-strain in the unconstrained state emerges upon subsequent heating. This is rationalized on the basis of a mechanism which takes into account the influence of stress on the formation of the austenite and the plastic deformation of martensite and austenite during constrained heating. Most importantly, the constrained reverse and forward transformations corresponding to the redformation of the oriented martensite and the formation of the stress-induced martensite and thermal martensite, respectively, lead to the subsequent two-stage recovery-strain and recovery-stress characteristics. Both the prestrain level and the constrained heating temperature play important roles in the phase transformations and thermomechanical characteristics of the TiNi SMA.

I. INTRODUCTION

PSEUDOELASTICITY, the shape-memory effect, and a high damping capability have made shape-memory alloys (SMAs) attractive as functional materials in engineering and medical applications.1,2 If a prestrained SMA is prevented from shape recovery during the transformation from martensite to austenite, a large stress of up to several hundred milli Pascals against the external constraint is generated. This stress is called recovery-stress, which is typically characterized by an almost linear increase with increasing temperature.3–6 For SMAs as actuators, the recovery stresses are usually used to overcome some external stress or strain. The SMAs have been applied not only as actuators, but also as reinforcement elements in smart composites or structures in recent years.7–13 It is well known that the thermoelastic martensitic transformation is sensitive to both stress and temperature. Thus, the constrained phase transformations of SMAs associated with recovery-stress are more difficult to understand than unconstrained transformation. The transformation induces the recovery-stress, which, in turn, affects the transformation. Up to now, a clear understanding of such constrained transformations and their influence on the subsequent thermomechanical characteristics of SMAs is still lacking.

The purpose of the present work is to investigate phase transformations and associated mechanical characteristics of a prestrained TiNi SMA during constrained thermal cycling. The constrained condition here refers to a constant uniaxial mechanical strain, which is kept constant and does not allow for shape recovery.

II. EXPERIMENTAL PROCEDURES

A commercial polycrystalline Ti-50.2 at. pct Ni alloy wire of 0.48 mm in diameter was supplied by the General Research Institute for Non-Ferrous Metals (Beijing, China). The material was annealed at 973 K in vacuum for 1.2 ks and then cooled in air. The martensite start and finish temperatures (Ms and Mf, respectively) and the reverse-transformation start and finish temperatures (As and Af, respectively) of the material, as measured by a differential scanning calorimeter (DSC), are 302, 287, 318, and 338 K, respectively.

In order to study the constrained transformation behaviors of a TiNi SMA, tensile deformation and constrained thermal cycling were imposed, as illustrated in Figure 1. The wires in the martensitic state were first deformed in tension and unloaded to a certain prestrain level (ε0), denoted as stage OAB, followed by repeated constrained heating to generate recovery stresses (denoted as stage BC). Prior to initial deformation, the specimen was cooled in liquid nitrogen to ensure a martensitic state. The DSC and recovery-strain measurements were performed to characterize the transformation of TiNi after constrained thermal cycling. A DSC apparatus, of the type TA INSTR 2910 (TA Instruments, New Castle, DE), was used at a heating and cooling rate of 10 K/min. The thermomechanical measurements were carried out using a thermal mechanical testing machine. This machine was equipped with an air bath with a temperature precision of ±1 K, and the gage length of the specimen was 50 mm.

III. RESULTS

A. Deformation and Martensite Stabilization

Figure 2 shows the tensile stress-strain curve of TiNi, and ε0 refers to the strain after unloading. The test is conducted...
at 293 K, which is 25 K lower than \( A_s \), so the specimen is martensitic because of the prior cooling in liquid nitrogen. Thus, this stress-strain curve can be divided into three parts, which correspond to the elastic deformation of the thermal martensite (stage I), martensite reorientation (stage II), and further reorientation and plastic deformation of oriented martensite (stage III), respectively.\(^{[14,15]}\) This value decreases with further increase of prestrain level.

These results are consistent with the results reported in the literature.\(^{[3±6]}\) It is well known that the recovery-stress of a SMA upon heating is due to the constrained transformation from oriented martensite to austenite. Thus, it is reasonable to consider that the constrained reverse-transformation continues up to 453 K. Since the \( A_s \) and \( A_f \) temperatures in the unconstrained state of the specimen with a prestrain of 6.6\% are 347 and 360 K, respectively, it can be concluded that the temperature span of the reverse-transformation under constraint shows an increase of at least 106 K (from 347 to 453 K), while that of the corresponding unconstrained state is only 13 K (from 347 to 360 K), i.e., the temperature span of the constrained reverse-transformation is widely enlarged.

B. Recovery-Stress

The evolution of recovery stresses with the prestrain levels is shown in Figure 4. It should be pointed out that a prestress of 50 MPa within the elastic limit of the TiNi alloy is applied to each specimen before heating to align the specimen. One can see that the recovery-stress steadily increases with temperature for all levels of prestrain. To a prestrain level of 6.6\%, the amount of recovery-stress at 453 K is 425 MPa, which represents the maximum value in our experiments; this value decreases with further increase of prestrain level. These results are consistent with the results reported in the literature.\(^{[11±6]}\) It is well known that the recovery-stress of a SMA upon heating is due to the constrained transformation from oriented martensite to austenite. Thus, it is reasonable to consider that the constrained reverse-transformation continues up to 453 K. Since the \( A_s \) and \( A_f \) temperatures in the unconstrained state of the specimen with a prestrain of 6.6\% are 347 and 360 K, respectively, it can be concluded that the temperature span of the reverse-transformation under constraint shows an increase of at least 106 K (from 347 to 453 K), while that of the corresponding unconstrained state is only 13 K (from 347 to 360 K), i.e., the temperature span of the constrained reverse-transformation is widely enlarged. Similar results can be found for the specimens with prestrain values from 2.9 to 8.6\%, as well as for prestrained TiNi SMAs under the constraint of composites.\(^{[12]}\)