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Effects of thermo-mechanical cycling on the strain response of Ni–Ti–Cu shape memory alloy wire actuator

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Abstract

The present paper deals with the strain response of Ni–Ti–Cu shape memory alloy (SMA) wire actuators on thermo-mechanical cycling (TMC). The characteristics of the actuators such as austenite (hot shape) remnant deformation and recovery strain undergo changes upon TMC. These changes are significant in the initial few cycles and the properties of SMA tend to reach a steady state on further cycling. It is believed that TMC induces defects in the microstructure and stabilizes the martensite/austenite phase. These in turn result in continuous change in strain response with the progress of TMC. It has been shown that for a stable strain response, the wire actuators need to be subjected to TMC at a higher stress than the working stress prior to application. Experiments were also conducted in order to minimize the number of TMC required for achieving stable strain response.

Keywords: Shape memory alloy; Ni–Ti–Cu; Thermo-mechanical cycling; Recovery strain; Transformation temperatures

1. Introduction

In recent years, there has been growing interest in the use of near-equiatomic Ni–Ti shape memory alloys (SMAs) as functional/smart materials for a variety of applications [1–8]. Applications like actuators, which require a short response time, are easier to realize using alloys with narrow hysteresis. In this respect, Ni–Ti–Cu ternary SMAs offer distinctive advantages over Ni–Ti binary SMAs [9,10].

During application, the SMA actuators are subjected to thermal cycling under a given load through the transformation range, which is generally referred to as thermo-mechanical cycling (TMC). The actuators are expected to perform the desired operation repeatedly without any deterioration in the strain response. Hence, the stability of the SMA upon TMC is an important parameter in designing the actuators [11–13]. Thermal cycling under an external stress is commonly observed to cause changes in the transformation temperatures (TTs), hot shape, recovery strain (RS), and recovery stress [14]. The reasons for such changes have been attributed to accumulation of defects, structural changes and stabilization of martensite/austenite phase in the material [14,15]. Studies have shown [10,15] that the changes in properties are quite significant during the initial few cycles and the material tends to get stabilized on further cycling.

The effect of TMC on the properties of SMAs and the methodologies adopted for stabilization of the properties are scarcely documented in open literature. One such study [16] recommended that cycling of NiTi for 30 times at 6% strain gives a stable strain response for strains less than 6%. In a similar study, Erbstoeszer et al. [17] have reported that TMC at a 30% higher stress than the working stress for 10 cycles followed by 80 stress free thermal cycles (SFTC) through the transformation range resulted in a better strain response.

The present paper deals with an experimental study wherein the strain response of Ni–Ti–Cu SMA wire actuators on TMC was determined. Attempts were also made to establish a training methodology to obtain a steady strain response from the first cycle onwards.

2. Experimental

The material used in this study was a ternary Ni–Ti–Cu alloy of nominal composition 44.5Ni–50.0Ti–5.5Cu (at.%) in the form of wire of diameter 0.5 mm. The wire was processed by multi-step cold drawing with intermediate annealing at 700 °C

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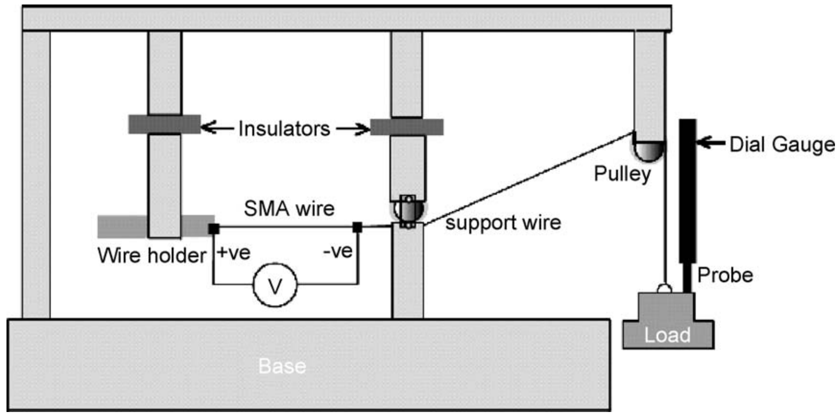

Fig. 1. Schematic of the thermo-mechanical cycling set-up.

for 10 min. For the present study, the specimens were taken from a 30% prior cold-worked wire annealed at 475 °C for 30 min followed by water quenching. The annealed wire had martensite finish (M_f) and austenite finish (A_f) temperatures of 33 and 58 °C, respectively.

The experimental set-up used for the study is shown in Fig. 1. The SMA wire was thermally cycled through the transformation range under a pre-determined static load. Resistive heating and forced air-cooling with cycle time of 60 s was used for all the TMC experiments. A dc current of 2 A was used for heating the wire to ~80 °C. These parameters were determined experimentally and were found adequate to ensure complete phase transformations upon heating and cooling. It may be noted that the M_f of the SMA wire was 10 °C above the ambient temperature (23 °C) and therefore, air-cooling to room temperature was sufficient to ensure complete martensitic transformation. The strain on the specimen was monitored using a dial gauge of resolution 0.05 mm. The length of the wire for each test was about 200 mm. In a few experiments, the SMA wires were pre-strained to predetermined values prior to TMC. The pre-straining was done using a universal testing machine. The transformation temperatures (TTs) were determined using a differential scanning calorimeter (DSC). During DSC scans, a constant heating/cooling rate of 10 °C/min was employed. The TTs were determined during the second temperature scan in the DSC experiments. The first temperature scan was not considered to avoid the effect of stress-induced transformation in the material.

The stress–strain diagram for the wire was determined as per ASTM-E08M test standard. The tensile test was performed at room temperature at a strain rate of $2.5 \times 10^{-3}\ s^{-1}$. To generate the reference data, the wire specimens were subjected to TMC for 100 cycles at stress levels of 150 and 250 MPa. The results of these two experiments (Figs. 2 and 3) were used to determine the stress levels and the number of cycles required for subsequent experiments.

Three sets of experiments were conducted in the present study. The first set of experiments consisted of TMC of the SMA wires at higher stress levels, TMC step I, followed by TMC at a lower stress level, TMC step II. In the second set of experiments, the wires were pre-strained to different strain levels in the martensite phase and then they were subjected to TMC at

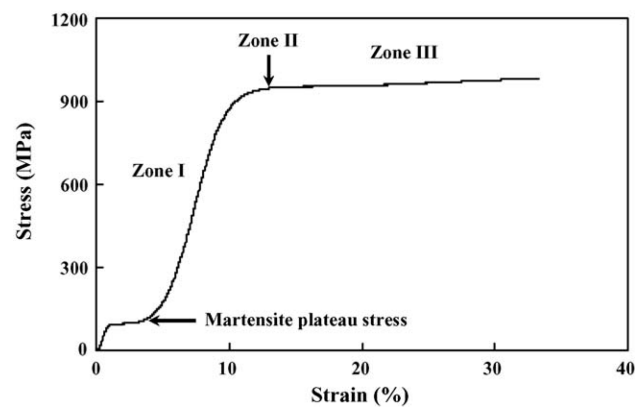

Fig. 2. Stress–strain diagram of Ni–Ti–5.5 at.% Cu SMA wire tested in martensite phase at 23 °C.

two stress levels. After pre-straining and prior to TMC, the wires were heated to a temperature $T > A_f$ so that the recoverable strain was fully recovered and the wires were left only with the plastic strain, present, if any. The pre-strain levels were selected such that they lie at three different zones in the stress–strain curve in the martensite phase (Fig. 2). Zone I is below the martensite yield point, zone II just above the yield point and zone III in the plastic range. In the third set of experiments, the wires were

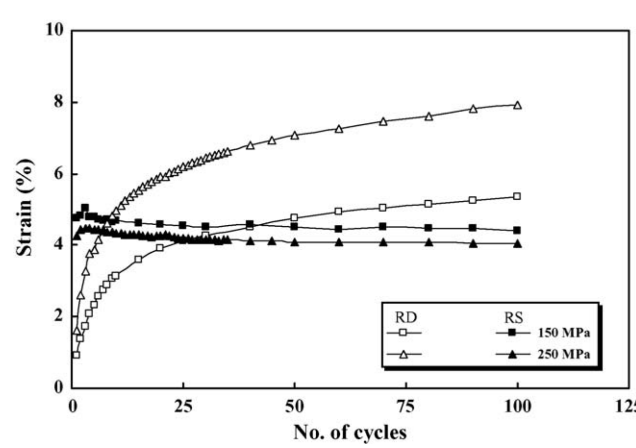

Fig. 3. Strain (RS and RD) vs. number of cycles plot of a Ni–Ti–Cu SMA wire actuator during TMC.