FUNCTIONAL FATIGUE PROPERTIES of TiNiZrSn BIOCOMPATIBLE SHAPE MEMORY ALLOY

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Abstract

Functional fatigue degrades the superelastic properties of shape memory alloys under cyclic loading. In the presence of geometric stress concentrations, the local stress fields are amplified resulting in local accumulation of irrecoverable strains and consequently loss of functionality. For the biocompatible TiNbZrSn system, grain size and solution treatment temperature play a major role in affecting the level of pseudoelastic strains and their evolution upon cycling. These aspects are quantitatively investigated in this work. Dogbone tensile specimens and samples with drilled circular holes are considered in this work and full field strain measurements are employed to quantitatively evaluate the localization in response leading to loss of functionality.

1. Introduction

Shape memory alloys (SMA) exhibit unique functionality that enables a wide range of applications across several industries, including biomedical. Depending on alloy composition, deformation temperature, and aging treatment, a SMA can exhibit a shape memory effect (SME) or/and superelasticity (SE). Many systems have been developed which exhibit such desirable properties, however, NiTi has received significant attention and remains the most investigated SMA. Despite its wide adoption across a wide range of applications, especially biomedical, there remain challenges related to the biocompatibility of the system with concerns over the release of the toxic Ni element into the body. The binary TiNb and ternary TiNbZr systems have been developed to address this limitation of NiTi. The mechanical (i.e., extreme rolling) and aging treatments that are necessary to induce SE properties in this class of materials induce defects along with residual stresses in the structure which impacts the material slip resistance and cyclic fatigue properties, both functional and structural. This work is focused on the functional fatigue properties of TiNbZrSn SE SMA in the presence of geometric stress concentration (i.e., drilled holes). Stress concentrations in the form of drilled holes, as an example, elevate nominal stress magnitudes resulting in a higher susceptibility for fatigue failure. In most metals, structural fatigue is induced following the generation and growth of microcracks. However, in SMA, cyclic loading can also trigger a loss of functional properties with continued cycling. Obviously, this loss of functionality diminishes the desirable ability of a SE SMA to exhibit large levels of reversible deformation. In this work, the effect of heat treatment and grain size on the functional fatigue properties of TiNbZrSn will be investigated. Full-field deformation measurements are utilized to make an accurate assessment of the localized SE strains in the vicinity of drilled holes along with the accumulation of irrecoverable strains.

2. Results

A TiZr20Nb11.5Sn2.5 ingot was cast using pure elements. The ingot was homogenized at 1100 °C for 24 hours in an Ar atmosphere. Following homogenization, the material was rolled to different levels (91% - 96.8% rolling). Tensile specimens having a 0.3×3 mm^2 and 8 mm gauge length were cut from the rolled sheets. Prior to testing, specimens were subjected to solution treatments at different temperatures (800 – 950 °C). The functional fatigue response, i.e., recovery and residual strains, were measured for standard dogbone samples and specimens having a 1.6 mm drilled hole. An example of the functional response for a standard tensile sample is shown in Figure 1. The magnitude of irrecoverable strains clearly depends on the applied strain levels. For applied strains less than ≈ 3%, the accumulation of irrecoverable strains with cycling is not significant beyond the first cycle.

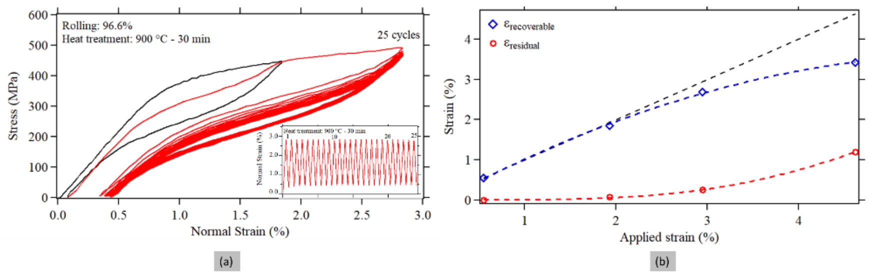

Fig.1 – (a) Cyclic stress-strain curves of a TiNbZrSn sample subjected to 25 loading cycles. The inset shows the applied strain history. (b) The evolution of recoverable strains ($\varepsilon_{recoverable}$) and residual strain with cyclic loading ($\varepsilon_{residual}$).

As noted above, this work is focused on the functional fatigue properties of TiNbZrSn in the vicinity of drilled holes. A schematic of the utilized specimen along with optical images of the undeformed and loaded sample are shown in Figure 2. To provide precise measurements of the developing strain fields, which are highly heterogeneous, full-field strain measurements were used to provide accurate information of all strain components following cycling loading, spatially. The contour map shown in2 was collected using Digital Image Correlation (DIC) and highlights the complex deformation field which develops during loading of a transforming SMA with geometric stress concentration. Similar to the preliminary results shown in Fig. 2, identical analysis will be conducted and analyzed over the life of the specimen.

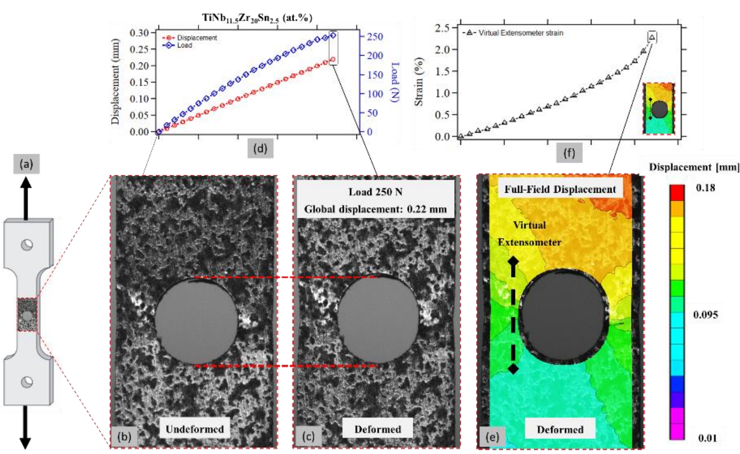

Fig.2 – (a) TiNbZrSn SMA specimen with drilled hole – loaded in tension. (b)-(c) Optical images captured before loading and at the maximin applied load, respectively. (d) The evolution of applied load and total specimen displacement. (e) Full-field contour plot showing the displacement field around the drilled hole region. The DIC virtual extensometer was used to get the strain in the vicinity of the hole. The evolution of extensometer strains is shown in (f) for the entire loading history.

3. Conclusions

The work is focused on the functional fatigue response of biocompatible TiNbZrSn SMA in the presence of a stress localization. The resulting grain size is strongly influenced by the level of cold rolling. In addition, solution treatment temperature and time influence the local stress field and consequently the transformation stress levels. The accumulation of irrecoverable strains (i.e., functional fatigue) is strongly influenced by such mechanical processing and thermal treatment. These effects are quantitatively studied in this work.

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