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Internal loops in superelastic shape memory alloy wires under torsion – Experiments and simulations/predictions

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ABSTRACT

Understanding torsional responses of shape memory alloy (SMA) specimens under partial or fully transformed cases with internal loops is of particular importance as the entire response might not be always utilized and only a portion of the entire response (internal loop) might be of significance to designers. In this work, we present experimental results of large complex loading and unloading torsional cycles which were conducted on superelastic SMA wires, under isothermal conditions with the purpose of elucidating the torsional internal loop response during loading and unloading. Such data hereto has not been available in open literature. Utilizing this data, we model the torsional response of superelastic SMA wires subjected to various loading and unloading situations that can result in different extents of transformation.

A thermodynamically consistent Preisach model (Rao and Srinivasa, 2013) captures such complex internal loops with a high degree of precision by modeling driving force for phase transformation vs. volume fraction of martensite relationships. This approach is different from capturing purely phenomenological stress–strain or stress–temperature Preisach models. The thermodynamic approach utilized here has broader predictive capability. The model predictions indicate good agreement with the internal loop structures even though only the outer loop information was used for model calibration. The addition of a single inner loop information for model calibration greatly improves the predictions.

1. Introduction

Shape memory alloy (SMA) components like wires, tubes and springs under torsion are being used in many applications due to their ability to recover large strokes and deliver near constant forces over large displacements (Ghosh et al., 2013; NDC; Rao and Srinivasa, 2013, 2014). During service, such components can be subjected to load reversals before complete transformation is achieved which may result in partial or complex hysteretic internal loops[1] either during the loading or unloading stage of the response (Khandelwal and Buravalla, 2011; Miyazaki and Otsuka, 1989). Capturing such internal loop responses is important from an application standpoint because in many cases, knowledge of the entire response proves to be unnecessary and only a partial internal loop might be of significance to designers or application developers (Bogue, 2009; Machado and Savi, 2003). For example, in civil engineering applications, SMA components are being used as seismic resisting systems due to their excellent energy dissipation and re-centering capabilities during which they can be subjected to repeated loading and unloading cycles at different loading rates and amplitudes (Song et al., 2006; Speicher et al., 2009; Saadat et al., 2002; DesRoches and Smith, 2004; Wilson and Wesolowsky, 2005; Williams et al., 2002; Rao and Srinivasa, 2013). Such repeated loading and unloading cycles may result in smaller hysteretic inner loops. For orthodontic applications, SMA wires and springs are employed to deliver constant forces over large strokes for space closure and tooth movement (Drake et al., 1982; Miura et al., 1986, 1988; Rao and Srinivasa, 2013). In some other biomedical applications, SMA components are employed for a certain part of the plateau regions over the transformation region and unloaded later resulting in partially transformed loops (Kapila and Sachdeva, 1989; Manhartsberger and Seidenbusch, 1996; El Feninat et al., 2002; Spinella et al., 2010).

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[1] An internal loop is a consequence of intermediate loading and unloading preceding complete transformation that results in smaller hysteretic responses which closely mimics the characteristics of outer loops that is fully transformed. The area of these smaller hysteretic loops depends on the extent of the loading and unloading level which the component is subjected to during service within the transformation regime (plateau region) (Khandelwal and Buravalla, 2011; Miyazaki and Otsuka, 1989).

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Understanding the response of SMA springs and wires subjected to torsional loading has been of significant interest among researchers (Saadat et al., 2002; Drake et al., 1982). As these SMA components twist under torsion, the phase transformation front propagates from outer fibers inwards to the core of the cross-section and its location is not known a priori (Tobushi and Tanaka, 1991; Rao and Srinivasa, 2013). In addition, because the shear strain is quite negligible at the core, a fully transformed case is only possible at high degrees of twist (Rao and Srinivasa, 2013; Mirzaeifar et al., 2011; Mirzaeifar et al., 2010). In partially transformed cases, one can expect the presence of an untransformed austenitic core due to small shear strains at the core (Rao and Srinivasa, 2013). It is thus important for designers to study such partially transformed cases and internal loops to predict SMA component responses under different extent of loading and unloading levels more accurately.

Torsional tests on SMA springs, wires/rods have been reported in the literature. Aguiar et al. (2010), Attanasi et al. (2011), Barwart (1996), Mirzaeifar et al. (2011), Miura et al. (1986, 1988) and Rao and Srinivasa (2013) have reported force – stroke relationships for SMA springs. Clearly, the springs were partially transformed in all the reported cases as there were no distinct upper and lower plateaus or elastic deformation of stress induced martensite (SIM) as observed under fully transformed cases (similar to tension load cases). However, data of fully transformed springs is scanty due to difficulty in testing compression/extension helical springs over large strokes.

On the other hand, only a few studies on understanding torque–twist relationships for SMA wires under pure torsion are available in the literature. Doaré et al. (2012) performed experiments on superelastic SMA wires under different angles of twists (see experimental results – Fig. 4 in Doaré et al., 2012) with the maximum twist in their tests being limited to 450° twist. However, from these test results it is unclear if a fully martensitic wire is obtained at higher twists as there was no elastic deformation of SIM observed in these experiments. Chapman et al. (2011) in their work studied the response of three superelastic wires with different diameters under torsion until failure and their results clearly illustrates that one can observe a fully transformed wire response (similar to pure tension responses) under higher degrees of twist (see Figs. 2 and 3 in Chapman et al., 2011). Prahlad and Chopra (2007) and Dolce and Cardone (2001a,b) have attempted to study torque–twist behavior of SMA rods under pure torsion for partially transformed cases. Some combined loading cases (tension–torsion) on SMA components like rods and tubes have also been reported in literature (Andani et al., 2013a; Grabe and Bruhns, 2008; Han et al., 2005; Lim and McDowell, 1999; McNaney et al., 2003; Sun and Li, 2002).

In all the available literature on the topic, simple torsional loading and unloading cases at different extent of twists is discussed. Understanding internal loop responses have been limited to tension loading cases (see Fig. 4 in Huo and Müller, 1993, Figs. 2, 4a and b in Lexcellent and Tobushi, 1995, Figs. 3–12 in Tanaka et al., 1994, Fig. 3 in Sittner et al., 1995, Fig. 6 in Liu et al., 1998, Figs. 3 and 4 in Sittner et al., 2000, Fig. 12 in Müller and Seelecke, 2001, Fig. 6 in Dolce and Cardone, 2001a, Fig. 3 in Ortın and Delaey, 2002, Fig. 3 in Matsuzaki et al., 2002, Figs. 4 and 7 in DesRoches et al., 2003, Fig. 5 in Ikeda et al., 2004, Figs. 1–4 in Savi and Paiva, 2005, Fig. 2–4 in Kumar et al., 2007, Fig. 6 in Heintze and Seelecke, 2008, Fig. 7 in Müller, 2012, etc. for some illustrations under tension loading case). The study of internal loops (under loading and unloading stages) in wires under torsional loading is not addressed.

In this paper, an effort to investigate the response of superelastic SMA wires subjected to torsional loading and unloading cases with internal loops is undertaken. The main emphasis here is on experiments and modeling of internal loops. An Instron micro-torsion apparatus is used to conduct various test cases. The shape of inner loops compared to outer/major loops is examined and the return point memory (RPM) or sink point memory (SPM) aspects in the torsional response is investigated (see Fig. 8 in Khandelwal and Buravalla, 2011 for an illustration under tension loading). RPM and SPM provides important information on the ability of SMA components to return back to its original unloading point upon completion of a smaller hysteretic loop and is of particular importance to designers. SMA components showing good RPM/SPM characteristics is a desirable feature that indicates minimal residual/irreversible deformations after repeated complete or partial transformations.

In the second part of the paper, following Rao and Srinivasa (2013), a thermodynamically consistent Preisach model is used to predict the response of twisted wires. The key idea in this model is the decomposition of the entire hysteretic response into a thermoelastic and a dissipative part using a two species Gibbs potential (Doraiswamy, 2010; Doraiswamy et al., 2011; Rao and Srinivasa, 2013, 2014; Rao, 2013). Quantities measured experimentally such as torque and angle of twist serve as input parameters to the model. By doing so and rather than solving for non-homogeneous shear stresses across the specimen cross-sections (Rao and Srinivasa, 2013; Rao, 2013), direct torque–twist relationships at the component level are modeled.[2] Models capable of predicting responses directly in terms of torque angle of twist would play a vital role in designing many SMA devices across engineering disciplines from both structural and control systems standpoint (Rao and Srinivasa, 2013, 2014; Rao, 2013).

Such a modeling approach also offers the advantage of being able to easily capture complex hysteretic responses with multiple internal loops both under load or displacement controlled experiments (Doraiswamy, 2010; Doraiswamy et al., 2011; Rao and Srinivasa, 2013, 2014; Rao, 2013). An interesting feature of the thermodynamic Preisach model is that it has some predictive capability and is not merely interpolative. Even for complex loading and unloading paths, one can predict the inner loop behavior with reasonable accuracy by using the outer loop data alone with no additional requirements. This means that a single loading/unloading cycle is all that is required to calibrate the model and can be used to simulate other complex loading-unloading paths with sufficient fidelity, a useful feature from a designer point of view.

The paper is organized as follows: in Sections 2 and 3, details on the material, apparatus and experimental protocols are presented. Various partially transformed cases obtained under different loading and unloading scenarios are discussed in Section 4. In Section 5, a two species Gibbs potential is formulated to obtain relationships between the thermodynamic driving force and the volume fraction of martensite using an additive decomposition. Section 6 discusses the details of implementing a discrete Preisach model to capture the driving force-volume fraction of martensite relationship which represent the purely dissipative part of the response. In Section 7,

[2] The common modeling approach in torsion literature is to replace normal stresses/strains/elastic moduli in 1D constitutive models by its shear counterparts namely shear stresses/strain/shear moduli (Aguiar et al., 2010; Paiva et al., 2005; Savi and Paiva, 2005; Rao and Srinivasa, 2013) or to reduce general 3D constitutive relationships to special 1D pure shear case and use a von Mises equivalent stress approach due to lack to full 3D experimental data (Mirzaeifar et al., 2011, 2010; Chapman et al., 2011). Andani et al. (2013b) and Andani and Elahinia (2014) have also made efforts to compare models of SMA behavior with non-proportional tension–torsion loading paths. Not surprisingly, the use of a simple von Mises equivalent stress approach have been found wanting and other definitions of equivalent stresses and strains have been proposed with resulting improvements in the response. However, the bulk of these cases do not deal with internal loops and partially transformed cases. The model presented in this paper, shares the basic Gibbs potential based formulation of Andani and coworkers but differs in the way in which the martensitic volume fraction evolves.