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Evolution kinetics in Shape Memory Alloys under arbitrary loading: Experiments and modeling

Vidyashankar Buravalla *, Ashish Khandelwal

Global General Motors R&D, India Science Lab, ITPB, Whitefield, Bangalore 560 066, India

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ABSTRACT

An important aspect of modeling Shape Memory Alloy (SMA) behavior is the description of evolution kinetics as a function of thermomechanical driving forces. Due to path dependency in SMA behavior, it is essential to have appropriate memory in the model. This becomes critical during incomplete transformations due to load fluctuations frequently encountered in real world applications. In this work, experiments are conducted on SMA wires to investigate the material behavior under fluctuating thermal and mechanical loads. The nature of memory under such transformation is discussed to motivate the modeling effort. Based on the concept of thermodynamic dissipation function, a suitable memory parameter is introduced to capture the transformation process under fluctuating loads. In the context of phase diagram, the dissipation potential can be mapped to the width of the transformation region in the phase diagram. Hence, inside a transformation zone, the distance of a point on the load path from the finish boundary is used as a measure of dissipation, and hence as a memory parameter. This is used as an additional criterion for evolution. Using the existing cosine based function for the phase fraction, this additional criterion is shown to result in the behavior consistent with the experimental observations. The proposed criterion is used to describe both stabilized and non-stabilized hysteretic behavior and hence is quite general. Numerical simulations are carried out to predict the behavior of SMA under arbitrary thermomechanical loads. The salient differences in the proposed approach *vis a vis* existing models are highlighted. Predictions from the proposed model are compared with experimentally observed results for typical NiTi based SMAs for arbitrary thermomechanical loading. The proposed models are shown to adequately capture the observed behavior.

1. Introduction

Shape Memory Alloys (SMAs) exhibit two interesting characteristic behaviors viz., Shape Memory Effect (SME) and SuperElasticity (SE) or PseudoElasticity (PE) that are exploited in a variety of industrial, engineering and medical applications (Bernardini and Pence, 2002a; Friend, 2001; Duerig et al., 1990; Otsuka and Wayman, 2002). One of the challenges in the development of SMA based applications is an inadequate understanding of the phase transformation under arbitrary loading encountered in a realistic operating environment. Because of strong history or path dependency in the material response, the thermomechanical loading history has significant bearing on the SMA response and, in turn, on the response of the SMA device. To achieve good durability and reliability of SMA devices, it is important to address this issue of SMA response under arbitrary loading. As a step in this direction, in this paper, SMA behavior is assessed for certain types of arbitrary loading, during both superelastic and shape memory cycles.

From a review of pertinent literature, it is apparent that significant amount of effort has been put in to investigate SMA response under cyclic loads. Some of the important

* Corresponding author. Tel.: +91 80 4118 4088; fax: +91 80 4115 8562.
E-mail addresses: vidyashankar.buravalla@gm.com, vidyashankar_br@yahoo.com (V. Buravalla), ashish.khandelwal@gm.com (A. Khandelwal).

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experimental studies include Amengual et al. (1996), Bhaumik et al. (2008), Churchill and Shaw (2008), Eggeler et al. (2004), Erbstoeszer et al. (2000), Feng and Sun (2007), Hornbogen (2004), Matsuzaki et al. (2002), Otsuka and Ren (2005) and Tanaka et al (1996). Several authors discuss modeling of SMA response under such loading conditions (Bernardini and Pence, 2002b; Chi et al., 2007; Huo et al., 1993; Ivshin and Pence, 1994; Kishore Kumar et al., 2007; Matsuzaki et al., 2002; Wu et al., 1999). Most of the theoretical and experimental investigations pertain to superelastic loading and studies to elicit the response under combined thermomechanical loading are limited. A schematic of cyclic loading is given in Fig. 1 wherein different types of arbitrary load sequences are illustrated. Sequence **a** shows loading that induces complete transformation cycles. Sequence **b** includes load fluctuations that are either within a transformation zone or only into a dead zone. Sequence '**c**' shows the fluctuations that span both forward and reverse transformation zones. It is seen from literature that the fluctuations of type **c** lead to stable inner loops (Matsuzaki et al., 2002; Wu et al 1999; Kishore kumar et al., 2007). However, for loads of type **b** the behavior could be different. For instance, after reaching a particular load level, if there is partial unloading and reloading, the reloading does not necessarily induce further transformation. In a stable material, reloading will induce transformation only when the previously attained level is exceeded. However, in a non-stabilized or untrained material, any reloading can induce transformation. In general, most of the existing work considers only the arbitrary loads of type **a** and **c** (Fig. 1) which induce either full or partial (inner) hysteresis loops.

Some experiments to investigate the effect of stress free thermal cycling have also been reported (Airoldi et al., 1997; Madangopal et al., 1994; Zheng et al., 2004). The focus of these experiments was to highlight the aspect of thermal arrest memory seen in SMA and they do not discuss the nature of kinetics and any shift in transformation conditions due to such thermal arrests.

The focus of the present work is to investigate the nature of memory for arbitrary loads of type **b** (Fig. 1), which

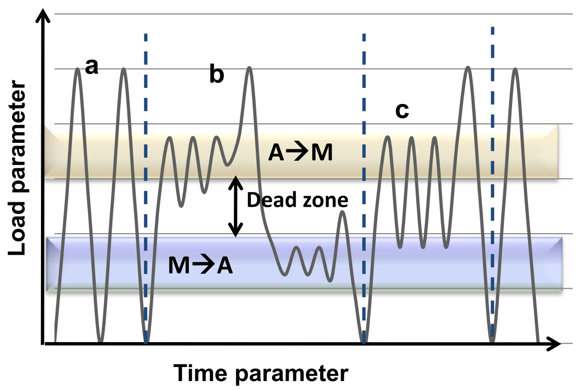

Fig. 1. Schematic load sequence involving three different types of load cycles; (a) shows complete load cycles, (b) shows cycles involving fluctuations that do not induce reverse transformation and (c) load sequence with fluctuations of load between two transformation zones leading to inner loops.

is not yet fully understood. Specific experiments are conducted to develop insights into the material response under such arbitrary fluctuations, both in temperature and in stress. A phase diagram based model is developed to capture the material response. The model predictions are compared with test data and several numerical studies are presented to highlight the SMA response under arbitrary load fluctuations. The term "arbitrary loading" in this paper refers to such (type **b** in Fig. 1) load fluctuations.

In Section 2, the experiments conducted to assess the material behavior under thermal and mechanical stress fluctuations are reported. Salient aspects of the material response are summarized to motivate the model development. Some of the experimental results are used to build the model and the rest are used to verify model predictions. In Section 3, key aspects of phase evolution under arbitrary loading and their modeling are discussed. Section 4 reviews some of the existing phase diagram based models for arbitrary loading. Section 5 presents the proposed model for describing kinetics under arbitrary loading using a phase diagram based approach and a suitable memory parameter. A comparative assessment of the existing models and the proposed model is provided in Section 6 using a standard case of superelastic behavior with and without arbitrary load fluctuations. Section 7 presents a comparative study between the experimental results and the predictions of the proposed models. Section 8 highlights the utility of the proposed approach to model the SMA response under realistic loading scenarios. The present work is summarized along with the major conclusions in Section 9.

2. Experiments to assess behavior under arbitrary loading

Conducting tests on SMAs, especially in thin wire form, under arbitrary thermomechanical loading is a challenging task. The following three different types of tests are conducted to elicit the material response under arbitrary thermomechanical loading of type Sequence '**b**' (Fig. 1).

1. Arbitrary thermal cycling under no stress.
2. Arbitrary thermal cycling under constant stress.
3. Arbitrary stress cycling at constant temperature.

Table 1 lists the three different NiTi based SMAs that are subjected to these type of arbitrary load excursions. The details of test procedures and the results are described below.

2.1. Stress free arbitrary thermal cycling

A few Differential Scanning Calorimetry (DSC) tests are run with interrupted thermal cycles using TA-Q2000 instrument. It may be noted that the DSC tests are normally performed over complete transformation cycles to determine the stress free transformation temperatures and the enthalpy of transformation, with a typical rate of 10 °C/min (refer ASTM standard F2004-03). However, in these tests, in order to minimize the effects due to