International Journal of Mechanical Sciences 96-97 (2015) 13–24

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Analysis of the deformation paths and thermomechanical parameter identification of a shape memory alloy using digital image correlation over heterogeneous tests

Yves Chemisky [a,*], Fodil Meraghni [a], Nadine Bourgeois [b], Stephen Cornell [c], Rachid Echchorfi [a], Etienne Patoor [a]

[a] *Arts et Métiers ParisTech Metz, LEM3 UMR CNRS 7239, Metz, France*
[b] *Université de Lorraine, LEM3 UMR CNRS 7239, Metz, France*
[c] *Department of Aerospace Engineering, Texas A&M University, 3409 TAMU College Station, TX 77843-3409, USA*

ARTICLE INFO

Article history:
Received 9 September 2014
Received in revised form
30 January 2015
Accepted 8 March 2015
Available online 14 March 2015

Keywords:
Identification
Optimization
Parallelization
Shape memory alloys
Heterogeneous tests

ABSTRACT

With the design of new devices with complex geometry and to take advantage of their large recoverable strains, shape memory alloys (SMA) components are increasingly subjected to multiaxial loadings. The development process of SMA devices requires the prediction of their thermomechanical response for which the calibration of the material parameters for the numerical model is an important step. In this work, the parameters of a phenomenological model are extracted from tests performed on specimens with non-uniform geometry, which induce heterogeneous strain fields carried out on specimens with the same thermomechanical loading history. The digital image correlation technique is employed to measure the strain fields on the surface of the specimen and to analyze the strain paths of chosen points. Finite element analysis enables the computation of numerical strain fields using a thermodynamical constitutive model for shape memory alloys previously implemented in a finite element code. The strain fields computed numerically are compared with experimental ones obtained by DIC to find the model parameters which best match experimental measurements using a newly developed parallelized mixed genetic/gradient-based optimization algorithm. These numerical simulations are carried out in parallel using a supercomputer to reduce the time necessary to identify the set of model parameters. The major features of this new algorithm are its ability to identify the material parameters which describe the thermomechanical behavior of shape memory alloys from full-field measurements for various loading conditions (different temperatures, multiaxial behavior, heterogeneous test configurations). It is demonstrated that model parameters for the simulation of SMA structures are thus obtained based on a reduced number of heterogeneous tests at different temperatures.

1. Introduction

Shape memory alloys (SMA) are utilized in a wide range of applications and have been incorporated in system with increased complexity. Their unique ability to recover substantial deformation when subjected to particular thermomechanical load made them very attractive and suitable for actuator devices and to replace complex assemblies. The development of new design solution, combining three-dimensional models along with an integration in finite element analysis (FEA) packages, has contributed to the appearance of shape memory alloys parts with complex geometrical shape.

It has been recently noticed that the development of modern computer design and analysis tools based on three-dimensional constitutive models is essential for the development process of SMA applications [36]. These models should be however calibrated from carefully obtained experimental data and advanced material characterization.

Indeed, new SMA structures are subjected to heterogeneous loading conditions, where the material locally undergoes non-proportional loadings. Once provided with the calibrated material parameters, three-dimensional constitutive models based on thermodynamics of irreversible processes can predict accurately and efficiently the behavior of such multiaxial, non-proportional loadings. A review of such models for SMAs can be found in Patoor et al. [38] for the constitutive modeling of a single crystal and Lagoudas et al. [28] for the constitutive modeling of polycrystals. Pioneer models have been improved over the years and have been

* Corresponding author.
E-mail address: yves.chemisky@ensam.eu (Y. Chemisky).

http://dx.doi.org/10.1016/j.ijmecsci.2015.03.007
0020-7403/

implemented in FEA packages [40,37,27,11,43,1]. Recent constitutive models have also focused on specific features associated with the unique behavior of shape memory alloys.

The evolution of transformation induced plasticity has been further considered for conventional SMAs by Bo and Lagoudas [7] and Lagoudas and Entchev [26]. The coupling between phase transformation and plasticity has also been considered in the literature [19,50,24] and at high temperature to account for viscoplastic effects [21,10]. Recent models have also focused on specific loading-path dependent behavior such as tension–compression asymmetry and anisotropy [11,43]. The design of SMA structures and the optimization of their characteristics rely now on finite element analysis. This constitutes powerful three-dimensional design solutions for SMA components subjected to complex loading. The accuracy of numerical simulations relies on the model ability to accurately account for uniaxial and multiaxial non-proportional loadings. However, these solutions require more advanced characterization techniques than the uniaxial tension or thermal analyses recommended by the ASTM standards [14,15]. Indeed, SMAs structural computations require necessarily the correct estimation of the model parameters including those related to the loading-path dependent multiaxial behavior and the characteristics of a specific alloy. The methodology specified in the ASTM standards was specifically designed for Nickel–Titanium in the biomedical industry, and may not be suitable for the identification of a model that aims at performing the numerical simulation of SMA structures. Moreover, since the methodology described in the ASTM standards does not give information about the characterization of the complete set of parameters for these models, the development of a reliable method to identify the parameters for SMA constitutive models is an important step to perform reliable numerical simulations for the design of SMA structures, regardless of the choice of a constitutive model. A traditional method is to systematically perform uniaxial tests in several direction, shear, combined tension/shear on a series of experiments to extract the features that are loading-path dependent. Also, a uniaxial stress–temperature diagram is constructed along with the uniaxial stress/strain/temperature response, and the parameters related to phase transformation are extracted from these graphical representation [25,22,20,11]. The most common procedure is to manually obtain the phase transformation data using a tangent intersection method [46]. However, several issues are associated with this method, as no objective criteria are utilized to assess the efficiency and the robustness of the method. This can lead to significant error when estimating the model parameters of a SMA material. For homogeneous tests, a recent method has been developed to identify the material parameters of a SMA from a set of experiments, utilizing a gradient-based inverse approach [34]. A similar approach has been used to determine the parameters of an SMA model from experimental data [49]. However, experimental characterization requires testing of several different types of specimens (tensile dogbone specimen, double shear specimens, thin tubes) to obtain the whole set of material parameters required for finite element (FE) simulations if tension–compression asymmetry and/or anisotropy induced by processing conditions is considered. In the case of Ni–Ti shape Memory Alloys, the processing of these specimens strongly influences the behavior [41] and thus the extraction of a unique set of parameters that represents the material behavior is not possible. Moreover, localization effects may be observed in specimens of simple geometry subjected to homogeneous loading, but the SMA device will not necessarily exhibit such effects, depending on its geometry and loading conditions. Thus identification of material parameters on specimens as similar as possible to the final product shall be preferred. Moreover, the design process is accelerated if the characterization requires only a few specimens. The identification procedure which utilizes full-field kinematical fields is an appropriate method for the identification of the set of material parameters for the purpose of SMA devices design. Such set of material parameters may include parameters characteristic of loading-path dependent behavior.

These considerations have motivated the development of an identification method to obtain the model parameter of a SMA constitutive law based on complex, heterogeneous loading conditions. Note that such a methodology is also necessary to properly analyze complex tests (i.e. multiaxial tests on samples with complex geometry), to be able to detect additional features, e.g. anisotropy and tension–compression asymmetry.

The requirements for such an identification procedure are summarized below:

(i) The identification procedure should be adapted to complex (multiaxial, non-proportional) thermomechanical tests utilized to characterize the constitutive behavior of materials.
(ii) The procedure should be fast enough to be of a practical interest for the identification of multiple parameters based on a reduced number of tests.
(iii) This procedure should be compatible with experimental observations, such as reaction forces and full kinematic field, measured at the surface of the sample using digital image correlation (DIC).

According to the last requirement, it is clear that the identification procedure relies on two-dimensional measurements. The identification of three-dimensional models requires additional assumptions about the anisotropic nature of their behavior, to be able to compute properly the out-of-plane response of SMA components (according to the plane where the kinematical field is measured). Identification methods coupled with kinematical fields measurement have been extensively developed in the last decades. The most used methods are described in the useful review work of Avril et al. [2]. These identification methods are classified into five categories, that are (i) the constitutive equation gap method (CEGM); (ii) the virtual field method (VFM); (iii) the equilibrium gap method (EGM); (iv) the reciprocity gap method (RGM) and (v) the finite element model updating (FEMU) method. The advantages and drawbacks of each method are described extensively in the review of Avril et al. [2].

The FEMU approach, proposed by Kavanagh and Clough [23], is most intuitive and has a lot of flexibility with regard to the definition of the cost function. This method can therefore be applied in a general framework, even if full-field displacement data with sufficiently sharp spatial resolution is not directly provided, which is necessary for the EGM and VFM methods [2]. Furthermore, the FEMU approach has the advantage to perform at the same time a parametric study of the material parameters, utilizing the numerical simulations performed for the identification, assuming that the design space has been sufficiently explored. Following these considerations, in this work a FEMU method is developed and coupled with an innovative combined genetic/gradient-based optimization algorithm. Since finite element analyses are necessary to compare the experimental data with the numerical simulations, a specific attention is devoted to the parallelization of such approach in a supercomputer.

Various optimization algorithms have been used in identification methods, i.e. deterministic algorithms such as gradient-based Levenberg–Marquardt algorithm [31,33], real space evolutionary-inspired, genetic algorithms or Bayesian statistical approaches [5]. The Levenberg–Marquardt optimization algorithm has been often adopted for the determination of material parameters for metals [45,32,16,13]. A hybrid algorithm that used an evolutionary algorithm combined with a gradient-based algorithm has been utilized by Chaparro et al. [9] to determine the parameters of an elastic–plastic constitutive model including an anisotropic criterion [3] coupled with a non-linear kinematical hardening [30]. The evolutionary algorithm was used to determine a good initial guess values for the gradient-based approach and therefore