Computational Materials Science 77 (2013) 93–101

Contents lists available at SciVerse ScienceDirect

Computational Materials Science

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

Density dependence of the superelastic behavior of porous shape memory alloys: Representative Volume Element and scaling relation approaches

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ARTICLE INFO

Article history:
Received 20 December 2012
Accepted 1 March 2013

Keywords:
Porous shape memory alloys
Scaling relations
Representative Volume Element
Simulations
Superelasticity

ABSTRACT

As the use of Shape Memory Alloys (SMAs) grows increasingly common in many industrial applications, the porous form of SMA is of particular interest as it associates both the shape memory effect and superelasticity with the characteristics of foam. However, numerical prediction of the mechanical response of SMA foam is very challenging due to the micro–macro nature exhibited by the material, as the porous microstructure is several orders of magnitude smaller than the overall dimensions of the macroscopic porous sample. To circumvent, or at least alleviate this computational weight, an attempt is made to describe the superelastic behavior of SMA foams using two approaches: Representative Volume Element (RVE) and scaling relation; the latter is based on modeling the fully-dense material with mechanical properties equivalent to those of its porous counterpart. This approach avoids direct modeling of the porous microstructure and thus contributes to a drastic reduction of the computational cost. A validation is made by comparing the numerical results obtained in this study with experimental results taken from the literature.

1. Introduction

The use of Shape Memory Alloys (SMAs) in porous form is highly attractive for many industrial applications, as the resulting material exhibits both the SMA mechanical properties, i.e. superelasticity and shape memory, and foam characteristics. Indeed, due to their additional benefits, foam materials are especially appealing since they exhibit several valuable characteristics such as low density, high permeability and desirable energy dissipation properties [21]. Selecting the degree of foam porosity is highly dependent on the final use of the material: from low pore volume fraction (PVF) in structural applications, up to 70% PVF for biomedical implants [4,5].

In this study, we focus our attention on SMA foams for biomedical applications, which are characterized by high porosity and open and interconnected pore structure to promote biological tissue ingrowth (see, for example, the study on titanium foam implants [6]. Several manufacturing techniques, such as Sintering Metal Powders or the Space Holder Method, are able to produce open-cell high PVF foams with random pore structure [17] suitable for medical applications.

From the materials science point of view, numerous studies have been performed to evaluate foam characteristics, but their numerical modeling, especially for the case of SMA foams, remains an active research domain. Specific numerical approaches such as the Unit Cell Finite Element Method [12,15] or the micro-mechanical averaging technique [7,13] cannot be used to model foams with high PVF and random and irregular pore structure – the types of most interest in this work.

The need for explicit modelling of the random pore structure has thus been demonstrated. This modeling can be realized by defining a Representative Volume Element (RVE) with dimensions that are larger than the ordinarily-considered microscale, while smaller than the macro or continuum scale. However, although the RVE enables the modeling of porous materials with lesser numerical cost than the micro–macro approach, the RVE approach is subjected to restrictions that make it unsuitable for modelling complex geometry, such as that of medical implants.

Therefore, we have decided to use the RVE approach as a first step, to define the Gibson–Ashby-like scaling relations. Within this approach, a property P of the foam material may be obtained as a function of the relative density using the following power law function:

$$\frac{P}{P_s} = C\left(\frac{\rho}{\rho_s}\right)^n \tag{1}$$

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http://dx.doi.org/10.1016/j.commatsci.2013.03.011

where the subscript s denotes the solid, i.e. fully dense, material, ρ the density, and C and n are the coefficients to be determined.

We also consider elastic and superelastic strains, on a micro-scale level, and explicitly excluding plasticity and damage accumulation. The validity of this scaling relations approach is then restricted to small and medium macro-scale deformations.

The paper is organized as follows. In Section 2, the Representative Volume Element (RVE) models of porous SMAs are described. The results obtained with the RVE model are then used to calibrate the parameters of the scaling relation approach (Section 3). In Section 4, the results obtained with the scaling relation approach are discussed and compared with the experimental data taken from the literature. Our conclusions are presented in Section 5.

2. Computational setup

2.1. SMA constitutive model

All the computations are performed using the commercial finite element software Ansys 14. The SMA model used is the one already implemented in [1], based on the work of [3]. Hereafter the model is briefly summarized and the interested reader is invited to refer to [3] for more information.

The material model implemented here considers the non-linear behavior occurring during the reversible phase transformation from Austenite to Martensite ($A \rightarrow M$ on Fig. 1) or from Martensite to Austenite ($M \rightarrow A$ on Fig. 1). For the sake of clarity, we adopt the following convention concerning the exponents or subscripts: A, M, AM and MA refer, respectively, to Austenite, Martensite, Austenite to Martensite and Martensite to Austenite phase transformations. It is assumed that the material behavior does not show any permanent strain and that the material is perfectly isotropic. Fig. 1 depicts the five constants used to model the SMA behavior:

- σ_s^{AM} is the starting stress for the phase transformation from Austenite to Martensite.
- σ_f^{AM} is the final stress for the phase transformation from Austenite to Martensite.
- σ_s^{MA} is the starting stress for the phase transformation from Martensite to Austenite.
- σ_f^{MA} is the final stress for the phase transformation from Martensite to Austenite.
- ε_L is the maximum superelastic strain.

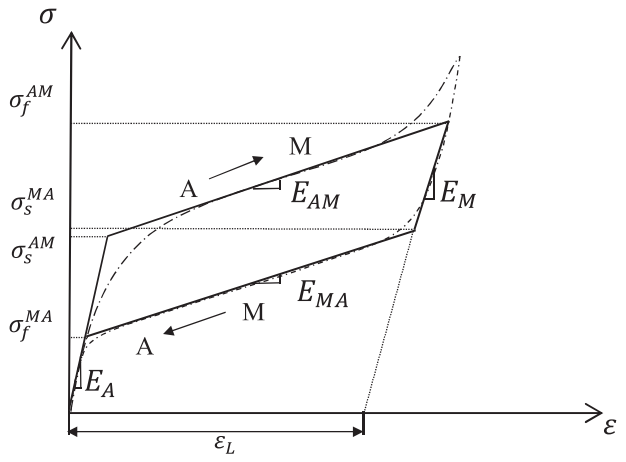

Fig. 1. Schematic of superelastic behavior (dash-dot line) with the Ansys model (plain line) and its parameters: σ_s^{AM}, σ_f^{AM}, σ_s^{MA}, σ_f^{MA} and ε_L; EA, EAM, EM, EMA, representing the corresponding Young's moduli.

Note that, along with the SMA constitutive model, the isotropic elastic Austenite model parameters (Poisson's coefficient and Young's modulus, the latter depicted by E_A in Fig. 1), must be filled out. To complete the model presentation, E_{AM}, E_M and E_{MA} moduli can also be used for the model description, as shown in Section 3.

Throughout the present article, porous SMA material will be defined by the parameters summarized in Table 1. The stress–strain response of a fully dense material calculated with the Table 1 parameters is shown on Fig. 2. Note that to reduce the number of iterations required to complete phase transformation, ε_L is set to 0.01, which is approximately 1/10 of the Ti–Ni superelastic range. No difference is made between tension and compression.

2.2. RVE approach: RVE size and characteristics

The porous material studied here exhibits a randomly defined porosity in terms of pore shape, size and distribution. As stated in the previous section, there is no means available to avoid the explicit representation of the porous microstructure while tracking the overall response of the material. To attenuate the numerical weight of such a micro–macro approach, one could apply specific numerical strategies to allow the macroscale behavior to be reproduced with a reduced model size, the so-called Representative Volume Element (RVE) approach. In this study, the RVE is defined as the smallest cubic sample capable of simulating the macroscale response of SMA foams under specific boundary conditions.

First, we create a cubic finite element model exhibiting randomly-defined pores. To ensure a good connectivity between the elements, i.e. in order for them to share at least one face, the porous RVE is set as follows: a cubic domain is considered as an empty (without matter) lattice of cubic elements; the central element of the lattice is then defined as a matter element and the foam (matter path) is created by affecting the matter of the randomly-picked neighbour sharing a face with the affected element. Repetition of

Table 1
Material parameters of a fully dense SMA constitutive model.

Material parameters	Values
E_A (GPa)	42
ν	0.3
σ_s^{AM} (MPa)	100
σ_f^{AM} (MPa)	140
σ_s^{MA} (MPa)	60
σ_f^{MA} (MPa)	20
ε_L	0.01

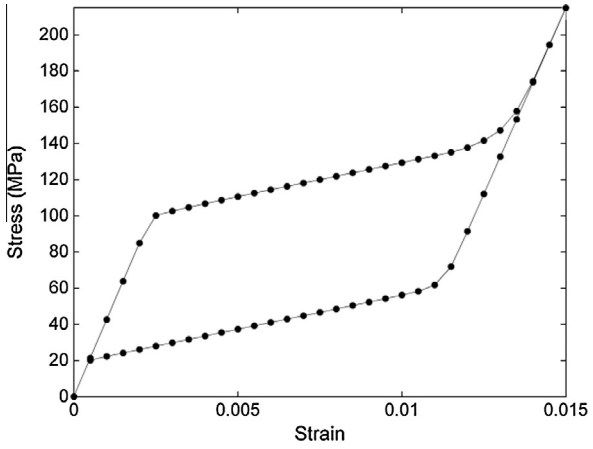

Fig. 2. Stress–strain curve obtained for a maximum strain of 0.015.