A Micromechanical Model for Textured Polycrystalline Ni-Ti Wires

Philippe Hannequart, Michaël Peigney, Jean-François Caron

SMST 2017: Conference Proceedings from the
International Conference on Shape Memory and Superelastic Technologies
May 15–19, 2017, San Diego, California, USA

A Micromechanical Model for Textured Polycrystalline Ni-Ti Wires

Philippe Hannequart
Arcora, Groupe Ingérop, Rueil-Malmaison, France
Université Paris-Est, Laboratoire Navier (UMR 8205), CNRS, Ecole des Ponts ParisTech, IFSTTAR, 77455 Marne la vallée, France
philippe.hannequart@enpc.fr
Michael Peigney
Université Paris-Est, Laboratoire Navier (UMR 8205), CNRS, Ecole des Ponts ParisTech, IFSTTAR, 77455 Marne la vallée, France
Jean-François Caron
Université Paris-Est, Laboratoire Navier (UMR 8205), CNRS, Ecole des Ponts ParisTech, IFSTTAR, 77455 Marne la vallée, France

Introduction

Thermomechanical models for shape memory alloys (SMA) can be categorized into two types. On the one hand, phenomenological models are based on thermodynamic considerations and enable to study SMA at a macroscopic level. They have been developed for one-dimensional [1] and for 3-dimensional structures [2]. On the other hand, micromechanical models rely on a description of the microscopic crystalline composition in order to compute the macroscopic response. They consider the occurrence and deformation of different martensitic variants inside a single crystal and/or the distribution of oriented crystals inside a polycrystal [3]. However, most micromechanical SMA models are computationally intensive and can only hardly be implemented in engineering codes to model smart structures including SMA wire actuators. Most models of this category are 3-dimensional, but some attempts at developing a simplified one-dimensional model have been made [4]. This research aims at providing a computationnaly efficient one-dimensional micromechanical model for polycrystalline Nickel-Titanium (Ni-Ti) wires, taking their 3-dimensional texture into account.

Model

The framework of non-smooth thermomechanics, with constrained internal state variables describing the different martensitic variants [6], is adopted here. The material evolution derives from the minimization of a free energy with the addition of a dissipation potential describing the hysteresis. It has been shown that the texture of polycrystalline shape memory alloys has a strong influence on their macroscopic thermomechanical behavior [3,5]. In the model considered, the texture is described by the list of crystalline orientations along with their volume fraction. Each crystalline orientation is characterized by two internal state variables: the volume fraction of self-accommodated martensite, and the volume fraction of the most favorably oriented martensitic variant (with respect to the loading direction). The influence of the 3-dimensional texture is thus considered in the one-dimensional mechanical response of the wire in traction.

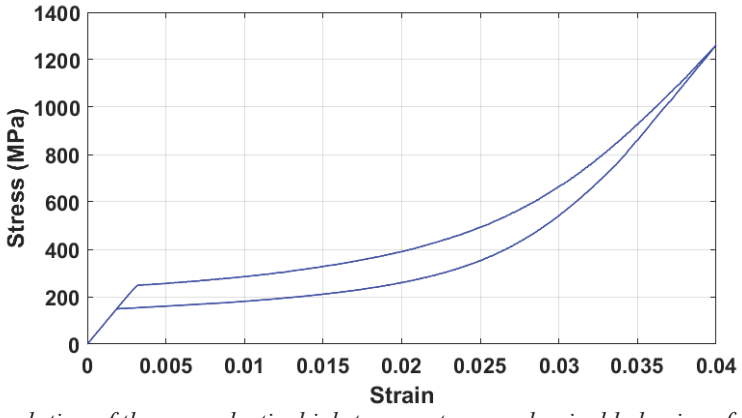

Figure 1: MATLAB Simulation of the superelastic, high-temperature mechanical behavior of a polycrystalline Ni-Ti wire under uniaxial traction

Numerical implementation

The model has been implemented numerically in an efficient computational tool. The time discretization of the evolution problem leads to a constrained and nonquadratic optimization problem to be solved at each point. That local incremental problem can be recast as a Linear Complementarity Problem (LCP) by using a procedure originally introduced in [7] for multi-variant, single crystals. That reformulation allows one to take advantage of existing interior-point algorithms which are known to be very efficient. A MATLAB code has first been written to perform preliminary simulation tests. A user-material subroutine (UMAT) has then been developed for the finite element software ABAQUS, allowing one to simulate the response of 3-dimensional structures embedding shape memory alloy wires (such as actuators).

Results

Several thermomechanical loading histories have been tested numerically to test and validate the proposed approach. The proposed model is able to capture the main features of the material response, such as superelasticity, self-accommodation and reorientation of martensite, as well as the one-way shape memory effect. Most crucially, the model is able to capture the nonlinear hardening that is often observed in the stress-strain response, both in the superelastic, high temperature regime, and in the low temperature regime. In Fig. 1 is presented the simulated stress-strain response of a polycrystalline wire under traction, in the superelastic regime. The texture is assumed to be isotropic in this simulation. The nonlinear hardening observed in Fig.1 is a direct consequence of the polycrystalline nature of the material. In all tested cases, the proposed numerical strategy leads to a significant gain both in computation time and robustness compared to classical constrained optimization algorithms.

Conclusions

A computationally efficient micromechanical model for SMA wires has been set up. The model parameters can be inferred from any given typical texture data of annealed Ni-Ti wires. The model can be used to simulate the response of smart structures containing SMA wires as actuators. Several experiments on Nickel-Titanium wires are currently carried out to calibrate and validate the model.

Acknowledgments

This work has been partially funded by Arcora & Ingérop Group and by ANRT under CIFRE grant No 2015/0495.

References

[1] Brinson, L.C., “One-dimensional constitutive behavior of shape memory alloys: thermomechanical derivation with non-constant material functions and redefined martensite internal variable” *J. Intel. Mat. Syst. Str.*, Vol. 4 (1993), pp. 229-242.

[2] Souza, A.C. *et al.*, “Three-dimensional model for solids undergoing stress-induced phase transformations” *Eur. J. Mech. A-Solid*, Vol. 17 (1998), pp. 789-806.

[3] Thamburaja, P., Anand, L., “Polycrystalline shape-memory materials: effect of crystallographic texture” *J. Mech. Phys Solids*, Vol. 49 (2001), pp.709-737.

[4] Nae, F.A., Matsuzaki, Y., Ikeda, T., “Micromechanical modeling of polycrystalline shape-memory alloys including thermo-mechanical coupling” *Smart Mater. Struct.*, Vol. 12 (2002), pp. 6-17.

[5] Shu, Y. C. and Bhattacharya, K., “The Influence of Texture on the Shape-Memory Effect in Polycrystals” *Acta mater.*, Vol. 46, No. 15 (1998), pp. 5457-5473.

[6] Frémond, M., Non-Smooth Thermomechanics, Springer (Berlin Heidelberg, 2001)

[7] Peigney, M., Seguin, J.P. and Hervé-Luanco, E., “Numerical Simulations of Shape Memory Alloys Structures Using Interior-Point Methods” *Int. J. Solids Struct.*, Vol. 48, No. 20 (2011), pp. 2791-2799.