11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
July 20–25, 2014, Barcelona, Spain

SIMULATION OF MECHANICAL BEHAVIOR OF NITI SHAPE MEMORY ALLOYS AND THEIR APPLICATIONS

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Key words: *Shape memory alloys, Constitutive modeling, Non-proportional loading, Superelastic helical spring, NiTi stent.*

Shape memory alloys (SMA) are metallic materials exhibiting unusual properties of being able to sustain and recover large strains and to remember the initial configuration and return to it with temperature change. These properties arise from a rearrangement of the crystal lattice associated with the so-called martensitic phase transformation, which can be induced by variation of temperature and/or variation of the applied mechanical load. Moreover, specific types of internal structure of the martensitic phase can develop depending on the loading conditions. These phenomena give rise to a very complex thermomechanical behavior, which classifies SMA into the group of so-called smart materials and makes them attractive for utilization in applications. The need of realistic simulations of SMA applications demands precise understanding and description of constitutive behavior of these alloys. For capturing the processes, which occur in the material at microscopic level (phase transformations, premartensitic transformations, martensite domains reorientation) and have an impact on at macroscopic level (inelastic strain), macroscopic thermomechanical models developed within the continuum mechanics generally introduce internal variables. These variables extend description of thermodynamic state in a material point and, as like as external variables (stress, strain, temperature), they appear in thermodynamic potential (energy function) and, most importantly, they allow to capture dissipation connected to the internal processes.

In this contribution, we present a novel 3D mathematical model for description of NiTi SMA, which was proposed after extensive experimental study of NiTi behavior under non-proportional loading [1]. The thermomechanical framework of generalized standard solids was suitable for model construction. The model was defined in three steps:

1. Description of state of the material by choice of internal variables – two scalar variables describing progress of premartensitic R-phase and martensitic transformation with one tensorial variable for martensite transformation strain were chosen as internal vari-

ables. Suitable constrains of these variables allowed to capture both tension-compression asymmetry and anisotropy of martensitic transformation.

2. Formulation of function of Helmholtz free energy – this function describes two dominating contributions, elastic energy and chemical energy terms.

3. Formulation of dissipation function – the formulation of the dissipative mechanism is of key importance in SMA model derivation as this function controls mutual interplay of martensitic transformation and reorientation and dominantly affects the simulated evolution of material internal structure. The proposed rate-independent form of dissipation coupling martensite transformation and reorientation processes is the most important novelty of the presented model.

Based on the mathematical analysis [2], we developed a suitable numerical approximation of the model, which was used for implementation into the finite element software Abaqus in the form of a User MATerial subroutine (UMAT). The subroutine was developed with respect to the time incremental minimization problem, determined by solving appropriate minimization problem by Nelder-Mead minimization algorithm. By this way, we avoid detecting of activated mechanism, which is the first step of commonly used elastic-predictor inelastic-corrector return map procedures.

Numerical simulations confirm very good predictive ability of the model - superelasticity, martensite deformation, R-phase transitions, one-way shape memory effect, martensite stabilisation by deformation and evolution of transformation hysteresis with temperature are captured. Especially, the model is very accurate in simulation of material response in non-proportional loading, which will be demonstrated by comparison of simulated and experimental results on combine tension-torsion tests on NiTi wires. Models of NiTi applications presented in this talk will further demonstrate the good predictability of the model. Comparison of simulated and experimental behavior of NiTi helical spring [3] and NiTi braided stents [4] will be shown and discussed.

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