ESOMAT 2009, 08002 (2009)
DOI:10.1051/esomat/200908002

Modeling of Two-dimensional Thermomechanical Loading of NiTi Wires

Miroslav Frost[1,2] and Petr Sedlák[2]

[1] Mathematical Institute, Charles University in Prague, Sokolovská 83, 18675 Praha 8, Czech Republic
e-mail: mfrost@it.cas.cz
[2] Institute of Thermomechanics, v.v.i., Academy of Sciences of the Czech Republic, Dolejškova 5, 18200 Praha 8, Czech Republic

Abstract. Results of simulations obtained by model iRLOOP for the Roundrobin SMA Modeling are briefly described and discussed.

1 The Two-dimensional Model

Thin wires from NiTi shape memory alloys exhibit outstanding thermomechanical properties which makes them suitable for a wide range of new medical and engineering applications. When these structures are mechanically loaded, multiple deformation modes involving tension, compression, torsion and bending usually occur. However, due to specific properties of thin wires the complex behavior can be effectively simulated by two-dimensional approach in many cases.

The proposed model consists of two interlinked algorithms – the first simulating the tension-compression response, the other simulating the shear mode – which are used simultaneously. The algorithms are twinned, i.e. the torsion algorithm was derived from the simple one-dimensional (tension-compression) model iRLOOP by reinterpretation of variables and parameters. Driving forces for martensitic transformation in the two algorithms are mutually independent (independent interface evolution concept) and simple assumptions on coupled strain evolution are made.

The 1-D iRLOOP algorithm determines the martensite volume fraction (MVF), ξ, from the value of driving force, ϕ, i.e. $\xi = \xi(\phi)$. The form of driving force is based on Clausius-Clapeyron equation coupling stress, σ, and temperature, T, with a constant, s, called the transformation coupling constant in this paper; $\phi(\sigma, T) = \sigma/s - T$. The transformation kinetics functions of complete transformation (TKF) obtained from experiments are input parameters to the model. To capture specific processes connected to transformation [1], TKF are decomposed into hysteretic, ξ^{h}, and non-hysteretic, ξ^{nh} parts, see fig. 1. A modification of hysteresis model proposed by Bouvet et al. in [2] is then used for description of incomplete transformation kinetics. A distribution of transformation strain inside the material element is introduced in order to include the processes of reorientation/detwinning in the model: a function representing the dependence of transformation strain of martensite on stress is denoted by $e(\sigma)$.

Detailed description of model iRLOOP can be found in [3,4]. The two-dimensional extension including discussion of its physical motivation is described in [5]

2 Parameters Identification

All scalar parameters corresponding to material properties and their values used in the Roundrobin simulations are listed in table 1. These parameters can be determined from one experimental

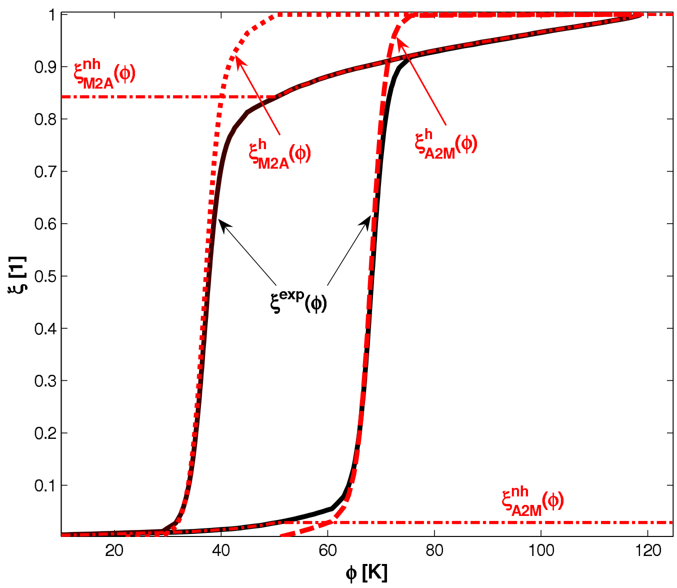

Fig. 1. An experimental major transformation functions, ξ^{exp}, are marked with full (black) line. Their decomposition to hysteretic parts, $\xi^{\text{h}}_{\text{A2M}}$ and $\xi^{\text{h}}_{\text{M2A}}$, is marked with dashed (red) line and to non-hysteretic parts, $\xi^{\text{nh}}_{\text{A2M}}$ and $\xi^{\text{nh}}_{\text{M2A}}$, with dash-dot (red) lines.

Table 1. Material parameters (scalars) entering the model and their values used in the Roundrobin simulations. M and A stands for martensite and austenite, respectively.

Parameter	Value	Unit	Meaning
A_{f}	278	[K]	finish temperature of M to A transformation
E^A	50	[GPa]	Young (elastic) modulus of A
E^M	40	[GPa]	Young (elastic) modulus of M
G^A	17	[GPa]	shear modulus of A
G^M	14	[GPa]	shear modulus of M
s_{ten}	6.5	[MPa/K]	transformation coupling constant for tension
s_{sh}	5.5	[MPa/K]	transformation coupling constant for shear
Γ_{sh}	0.05	[1]	maximum transf. strain of tension-induced M in shear

stress-strain response in superelastic region measured together with recovery stress test starting at lower plateau, for instance, see fig. 2.

The parameters represented by functions in the model are summarized in table 2. These functions can obtained from several recovery strain experiments with different constant pre-stresses by procedure described in [3] in full details, see also fig. 3.

However, for better comfort and speeding up the parameters identification procedure an interactive graphical user interface (GUI) was developed in MATLAB® code. The material functions of the model were approximated by three types of basic functions (linear, quadratic and hyperbolic tangent). These analytic functions were parametrized by several easy-understandable scalar parameters which are to be entered by the user. Number of these parameters can be found in table 2 for each function. The user can load the experimental results to the GUI, adjust the parameters and see the comparison of experimental and simulated results immediately. Due to simultaneous visualisation of several types of simulations in the GUI (superelasticity loops, pseudoplasticity loops, recovery strain cycles) and built-in parametrized functions, various sets of experiments can be used for parameters identification procedure. Since different chemical composition and processing (heat treatment, training) usually lead to very different transformation and detwinning/reorientation kinetics in NiTi [6–8], the GUI opens a wide space for simple, rapid and effective modeling of various types of NiTi wires.

Table 2. Material functions entering the model and the number of scalar parameters used to evaluate them in the GUI. M and A stands for martensite and austenite, respectively.

Function	Meaning	No. of scalars
$\xi^{\mathrm{h}}_{M2A}(\phi)$	M to A transformation kinetics function, hysteretic part	1
$\xi^{\mathrm{h}}_{A2M}(\phi)$	A to M transformation kinetics function, hysteretic part	1
$\xi^{\mathrm{nh}}_{M2A}(\phi)$	M to A transformation kinetics function, non-hysteretic part	3
$\xi^{\mathrm{nh}}_{A2M}(\phi)$	A to M transformation kinetics function, non-hysteretic part	3
$e_{\mathrm{ten}}(\sigma_{\mathrm{ten}})$	dependence of transf. strain on tension for tension-induced M	8
$e_{\mathrm{sh}}(\sigma_{\mathrm{sh}})$	dependence of transf. strain on shear stress for shear-induced M	8

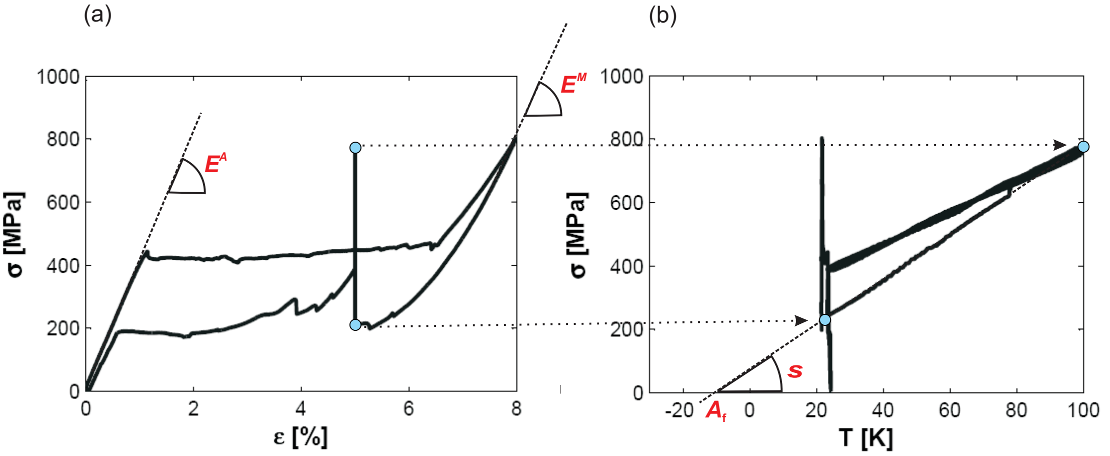

Fig. 2. Determination of the elastic moduli of austenite and martensite, austenite finish temperature and critical martensitic transformation slope (b) from recovery stress experiment (a).

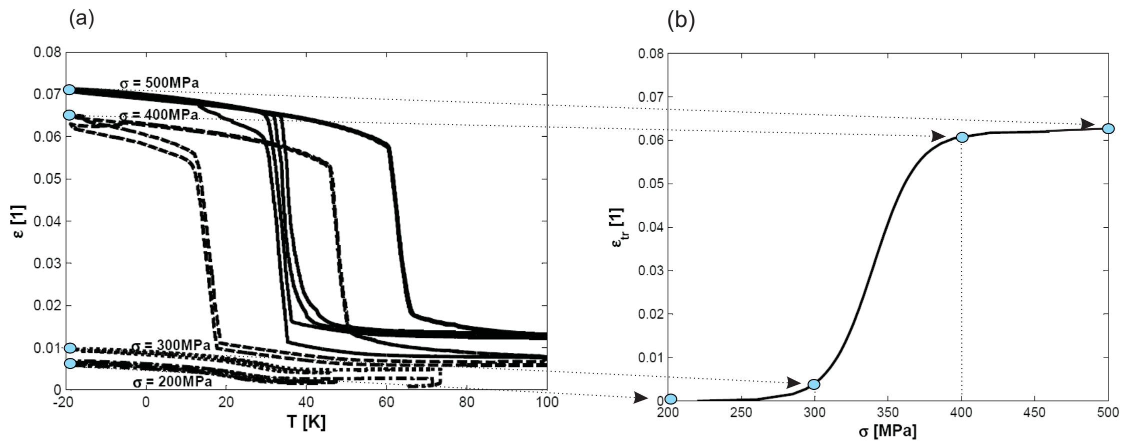

Fig. 3. Determination of the reorientation function $e(\sigma)$ (b) from recovery strain experiments (a).

3 Simulations & conclusions

The iRLOOP model and the parameters identification GUI were implemented in MATLAB® code. Torsion tests were performed using finite element approach taking advantage of the radial symmetry of the wire. Adapted finite element mesh consisted of 19 concentric cylindrical shells and 1 cylindrical element (core of the wire).

The parameters identification procedure was carried out using a different set of experiments than the set of experiments simulated in the Roundrobin. The model was able to reliably simulate stress-strain tests in tension and torsion (including superelasticity and reorientation/detwinning processes) for all testing temperatures. Also recovery stress tests and recovery strain tests were predicted with reasonable deviations. Some discrepancies occurred due to influence of R-phase transition in the wire, which is a process not included in iRLOOP model so far. The puzzling dependence of axial strain on radial displacement in tension-torsion tests were captured in a qualitative manner.

The model itself is also efficient in simulating one-way shape memory effect, tension-compression asymmetry and, especially, loading cycles with incomplete transformation, where the return point memory demonstrates itself. The model was developed as time- and rate-independent, therefore, training and aging effects are not covered as like as effects of plasticity.

This work was conducted in the FP6 integrated project UPWIND No. 019945, the ESF EUROCORES project MAFESMA GES3T/06/E002, the institutional project of IT ASCR, v.v.i., CEZ:AV0Z20760514. The research has also been supported by the Ministry of Education, Youth and Sports of the Czech Republic (MSMT) through grant No. 1M06031, the Grant Agency of the Czech Republic through grants No. 106/09/P302, No. 106/09/1573 and No. P108/10/1296 and the Grant Agency of Charles University in Prague through grant No. 306-10/251063. All the financial support is gratefully acknowledged.

References

1. L. C. Brinson, I. Schmidt and R. Lammering, J. Mech. Phys. Solids, **52**, (2004) 1549-71
2. C. Bouvet, S. Calloch and C. Lexcellent, Eur. J. Mech. A-Solid, **23**, (2004) 37–61
3. M. Frost, P. Sedlák, M. Sippola and P. Šittner, Smart. Mat. Struct., **19**, (2010) 94010
4. D. Vokoun, D. Majtás, M. Frost, P. Sedlák and P. Šittner, J. Mater. Eng. Perform., **18**, (2009) 706–10
5. P. Sedlák and M. Frost, Proceedings of the ASME 2009 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, **1**, (2009) 101–9
6. K. Otsuka and X. Ren, Prog. Mat. Sci., **50**, (2005) 511–678
7. Y. Liu, In *Smart Materials*, A. R. Wilson and H. Asanuma (Eds.), Proceedings of SPIE, **4234**, (2001) 82–93
8. H. Shahmir, M. Nili-Ahmadabadi and F. Naghdi, J. Mater. Design, (2010) *in press*