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THERMOMECHANICALLY COUPLED MODEL FOR NON-PROPORTIONAL LOADING IN SMAS

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Summary In this work, a new 3D thermomechanically coupled phenomenological model is proposed for SMAs. SMA behavior is described through several strain mechanisms, each associated with its proper internal variables. Forward and reverse transformation are allowed to take place simultaneously with martensite variants reorientation. This model is built to capture the particular behavior of SMAs when subjected to complex loading, namely non-proportional thermomechanical loading. The effect of thermomechanical coupling, related to dissipation and latent heat is examined by means of conducting simulations under various thermal conditions. The validity of the model is demonstrated by approaching experimental results of complex thermomechanical loading paths of SMA structures.

INTRODUCTION

In this work, a new 3D phenomenological model for SMAs is presented. A physical interpretation of the processes occuring inside a SMA grain is intended to be approached to redefine the principles of reorientation, forward and reverse transformation. This leads to the introduction of independent scalar rate variables which drive each of the three strain mechanisms. Accordingly, a robust formalism is presented within a thermodynamical framework, and based on a Gibbs free energy potential. Each internal variable is designed to evolve linearly with respect to one of those three scalar variables.

The model is implemented based on an open-source numerical simulation library [3] to conduct simulations of complex loading paths. The material parameters are calibrated using advanced identification methods and the thermomechanical aspects of the thermodynamic modeling are examined by simulating various thermal loading paths, e.g. isothermal and adiabatic. Such thermomechanical coupling accounts for the dissipation phenomena related to the three mechanisms, namely forward and reverse transformation, and reorientation.

THERMODYNAMIC MODELING

In the framework of thermodynamic phenomenological modeling, a Gibbs free energy potential governing the whole material behavior is defined. The main internal variables selected are the martensitic volume fraction ξ and three parts of the total inelastic strain $\boldsymbol{\varepsilon}^{\boldsymbol{T}}$, each driven by its respective inelastic mechanism. Forward transformation induces the evolution of $\boldsymbol{\varepsilon}^{\boldsymbol{F}}$:

$$\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{F}} = \dot{\xi}^F \boldsymbol{\Lambda}^{\boldsymbol{F}}_{\boldsymbol{\varepsilon}}(\boldsymbol{\sigma}) \tag{1}$$

Reverse transformation drives the evolution of $\boldsymbol{\varepsilon}^{\boldsymbol{R}}$:

$$\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{R}} = \dot{\xi}^R \left(-\frac{\boldsymbol{\varepsilon}^{\boldsymbol{T}}}{\xi} \right) \tag{2}$$

The effect of reorientation is given by evolving $\boldsymbol{\varepsilon}^{\boldsymbol{re}}$:

$$\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{re}} = \dot{p}^{re} \boldsymbol{\Lambda}^{\boldsymbol{re}}_{\boldsymbol{\varepsilon}}(\boldsymbol{\sigma}, \boldsymbol{X}) \tag{3}$$

The martensitic volume fraction ξ is always found by updating the increasing (Forward) ξ^F and decreasing (Reverse) part ξ^R:

$$\dot{\xi} = \dot{\xi}^F - \dot{\xi}^R \tag{4}$$

The scalar $\dot{p}^{re}$ is the magnitude of the strain that evolves within the martensitic volume which remains intact during transformation. The quantities $\boldsymbol{\Lambda}^{\boldsymbol{F}}_{\boldsymbol{\varepsilon}}$ and $\boldsymbol{\Lambda}^{\boldsymbol{re}}_{\boldsymbol{\varepsilon}}$ are orientation tensors and depend on the direction of stresses $\boldsymbol{\sigma}$ and the history of loading, carried within the backstress $\boldsymbol{X}$.

It is clear that the three scalar rates $\dot{\xi}^F$, $\dot{\xi}^R$ and $\dot{p}^{re}$ are the driving variables of the three mechanisms. When they have zero values, the respective strains do not evolve, since the mechanisms are not activated. For forward transformation, the criteria and the evolution laws implemented in [1] are taken in mind. For reverse transformation, a suitable criterion to ensure return to zero transformation strain when all the martensitic volume is recovered. A criterion imposing kinematic hardening is considered for reorientation. The backstress $\boldsymbol{X}$ attributes the kinematic feature to the reorientation behavior.

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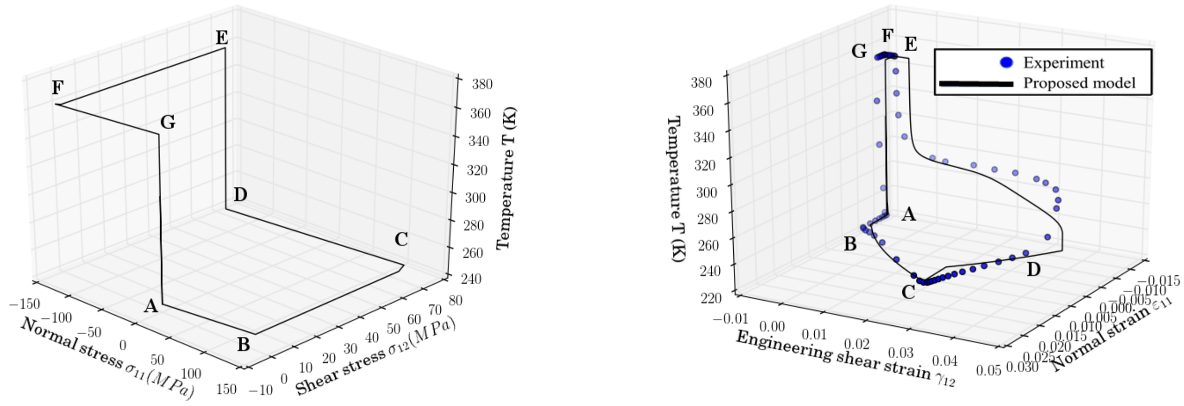
SIMULATION OF NON-PROPORTIONAL THERMOMECHANICAL LOADING

The validation of the model over experiments published in literature is performed. A thermomechanical loading consisting in tension, compression, torsion and temperature variation carried out on a NiTi thin-walled tube [2] has been simulated.

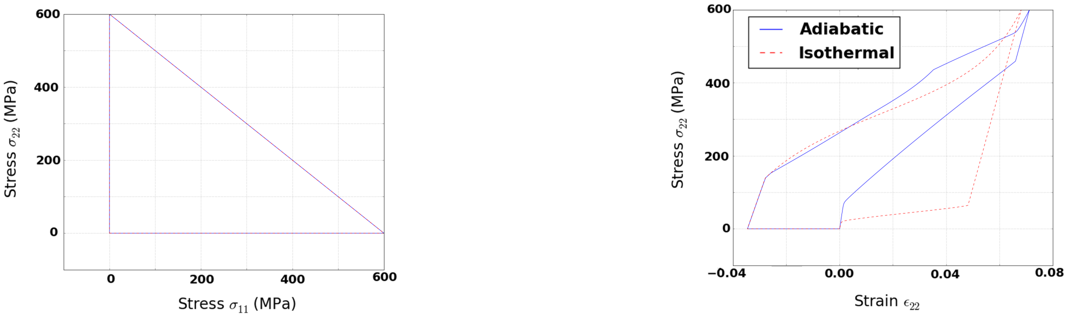


(a) Loading path

(b) Material and model response

Figure 1: Experimental results (points) and model reponse (continuous line) on the normal strain - shear strain - temperature diagram for the complex non-proportional thermomechanical loading taken from [2]

The implementation of the first law of thermodynamics has been carried out in the framework of multiple activated inelastic mechanisms. The effects of thermomechanical coupling are evident by comparing a simulation of a non-proportional loading under isotermal and adiabatic conditions. In the loading presented in Fig. 2, the initial temperature is 280K.



(a) Loading path

(b) Material and model response

Figure 2: Experimental results (points) and model reponse (continuous line) on the normal strain - shear strain - temperature diagram for the complex non-proportional thermomechanical loading taken from [2]

CONCLUSION

A novel thermomechanically coupled phenomenological model has been developped for SMAs. It succeeds in capturing material behavior under complex non-proportional thermomechanical loading, by taking in mind the simultaneous activation of transformation and reorientation. Its validity has been assessed in comparison with experimental results. The full implementation of the first law of thermodynamics allows the investigation of thermomechanical effects on the material response.

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