# Rate-dependent thermo-mechanical modelling of entropy changes in superelastic SMA

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## ABSTRACT

Superelastic shape memory alloys (SMAs) are unique smart materials with a considerable energy dissipation potential for dynamic loadings with varying strain-rates. The energy dissipation arises from a hysteretic phase transformation of the polycrystalline atomic grid structure. In fact, the nucleation from austenite to martensite phase and vice versa exhibits a strong thermo-mechanical coupling. In particular, the hysteresis depends on the latent heat generated by the austenitic-martensitic transformation and the convection of that heat. High strain rate interferes with the release of the latent heat to the environment and reduces the hysteresis surface. However, the degree of atomic disorder and accordingly the change in entropy influences the reverse phase transformation from martensite to austenite. In other words, the stability of the martensitic state affects the stress-level of the reverse transformation. Consequently, in phenomenological material models of SMAs, the effects of the rate-dependent entropy change must be considered to describe the energy dissipation behavior.

Existing material models derive constitutive equations for thermo-mechanical coupling by Clausius-Duhem inequality and Helmholtz free energy formulation. State-of-the-art free energy formulation considers an entropy difference between austenite and martensite. However, an additional strain-rate dependent entropy evolution can make constitutive models more precise. Hence, a free energy reformulation for solid-solid phase transformation is necessary to simulate the impact of martensite stability on the reverse transformation. Further experimental investigations and numerical developments are necessary to include strain-rate effects on the reverse transformation of superelastic SMA more precisely.

In this study, we conducted uniaxial tensile tests on superelastic nickel titanium (NiTi) wires. The experimental investigation included quasi-static and harmonic cycling excitations. Both trained and untrained wires with 0.127 and 0.200 mm diameters were investigated. The strain-rate effects were analyzed by measuring the stress-strain and temperature evolution for an excitation frequency range of 0-4 Hz in a strain amplitude range of 0-6 %. The results show that an increase in the excitation frequency causes a decrease in the size of the hysteresis area. Moreover, an increase in excitation frequency initiates the reverse transformation on a higher stress level and leads to a significantly increased slope. This effect is likely to result from the rate-dependent entropy change.

To incorporate the rate-dependent entropy change, we modified a one dimensional numerical model by way of an adjusted free-energy formulation for solid-solid phase transformation in superelastic SMAs [1]. In the present model, the observed effects of the excitation frequency on the reverse transformation are taken into account by calculating the rate-dependent entropy change. A comparison of the numerical results with the experimental data shows that the improved model calculates the dynamic superelastic hysteresis of SMAs more realistically.

[1] F. Auricchio and E. Sacco, “Thermo-mechanical modelling of a superelastic shape-memory wire under cyclic stretching-bending loadings”, *Int. J. Solids Struct.*, Vol. **38**, pp. 6123-6145 (2001)