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Gradient-based constitutive model to predict size effect in the response of SMA thin films

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ABSTRACT

For sufficiently small dimensions, the response of shape memory alloy (SMA) actuators is not independent of the sample size. The response of SMA single crystal micro/nanopillars is shown to depend on the size of the specimen. An increase in the critical stresses for the start and finish of austenite to martensite transformation is seen when reducing the diameter into the submicron region. In addition, the damping observed in a pseudoelastic cycle of a nanopillar is much higher than that of a counterpart SMA bulk specimen. This phenomenon is furthermore observed in SMA wires where the critical stresses for the start of martensite and austenite transformations are reported to increase for diameters <100 μm. Finally, the hardness of SMA thin films obtained from micro- or nanoindentation experiments was shown to depend on the indentation depth demonstrating an increased hardness for smaller indentation depths. SMAs have recently been used as a promising and high performance material for application in micro–electro–mechanical systems in the form of thin films/beams. Nano/microindentation experiments, on the other hand, are one the major experimental routines to establish properties of SMA thin film actuators. Assessing the functionality of such microactuators requires numerical modeling tools that can take into account the observed size effect. Size effect in the SMA response cannot be simulated using conventional constitutive theories, which lack an intrinsic length scale in their constitutive modeling. To enable such a property, a new nonlocal thermodynamically consistent constitutive model is developed, which in addition to conventional internal variables of martensitic volume fraction and transformation strain, contains the spatial gradient of martensitic volume fraction as an internal variable. This allows the introduction of energetic and dissipative length scales in the model. The transformation surface in such a theory will be obtained from the solution of a partial differential equation. In conventional formulations, transformation surface is an algebraic equation. A boundary value problem, in this case, contains the equilibrium equation with its standard boundary conditions as well as the PDE for the transformation and associated martensitic volume fraction. The developed gradient theory is used to analytically simulate the uniaxial stretching of SMA wires, pure bending of SMA beams, and compression response of SMA micro/nanopillars. SMA beams with larger thickness show a response closer to the classical (local) model prediction, which in the nondimentional sense, is independent of the thickness of the beam. In addition, the nano/microindentation process was studied using the developed constitutive model. The response of the SMA structures using the developed gradient theory depends on the size, being stiffer for smaller dimensions and harder for smaller indentation depths.