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Towards a phase-field approach for the fatigue assessment of Ni-Ti cardiovascular devices

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Abstract

Nickel-Titanium (Ni-Ti) shape memory alloy (SMA) represents the top choice for designing self-expanding cardiovascular devices enabling minimally invasive surgeries, thanks to its superelastic behavior arising from stress-induced phase transformation. Its primary applications include peripheral stents for treating lower limb occlusive pathologies and heart valve frames for replacing stenotic or insufficient native valves. Throughout their service life, Ni-Ti implants experience millions of fatigue cycles associated with physiological loading, resulting in complex multi-axial deformations. Ensuring the long-term reliability of these devices remains a multi-factorial challenge due to intricate designs, non-linear material behavior, and complex loading conditions. Current fatigue assessment methods routinely rely on total-life approaches that combine in vitro fatigue tests on surrogate specimens with computational simulations to evaluate device safety. However, this workflow presents several open issues related to the complexities of Ni-Ti behavior, preventing the use of standard and well-established practices. Simplistic fatigue criteria that overlook material complexities are typically adopted, without accounting for material defects or addressing the effect of crack tip phase transformation on damage. This work investigates a complementary predictive framework based on a computational phase-field approach to enhance the fatigue assessment of Ni-Ti cardiovascular devices, focusing on crack nucleation within a simplified one-dimensional setting. The model was developed by coupling the Auricchio-Petrini constitutive model for SMAs with a gradient damage model, adopting a variational approach. Model parameters were calibrated using quasi-static tensile tests on Ni-Ti multi-wire samples. Tensile fatigue tests on Ni-Ti multi-wire samples under several combinations of mean and alternate strains were simulated by exploiting the inherent structure of the model, allowing for damage accumulation under cyclic loads. The evolution problem was solved numerically, implementing an alternate minimization algorithm within a finite element framework. The model successfully distinguished between safe loading conditions corresponding to experimental run-out and critical conditions leading to failure. Predicted fatigue lives showed good agreement with experimental observations, highlighting the model's ability to provide reliable assessments in this simplified setting. Moreover, the model offers insights into Ni-Ti fatigue behavior, showing that localized phase transformation effectively delays fracture by diffusing the maximum damage across fully transformed regions. Future efforts will extend the model to higher-dimensional configurations and crack propagation scenarios, aiming to establish a robust predictive framework for Ni-Ti cardiovascular devices to lower the burden of experimental testing while enhancing device reliability.

Keywords:

Shape memory alloys failure prediction computational approach