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Phase field modeling of crack nucleation and propagation in martensitic micro–structures

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In this paper, a combined phase-field (PF) approach has been considered to model fracture behavior under martensitic transformation effects. The effect of temperature as another degree of freedom has been studied, which has not been taken into account in previous studies. The concept of thermodynamic driving force, the elastic energy, interfacial energy, heat transfer and the kinetics of phase field equations are introduced to obtain the fracture domain, the martensitic evaluation, the temperature field and displacements [1]. Due to the high amount of stress at the crack tip, the martensitic transformation can start and propagate through the austenitic structure. The internal stresses between martensitic and austenitic layers deviate the crack path, leading to changes in the martensitic formation [2]. In addition, temperature plays an important role in this phenomenon in two aspects; first of all a change in temperature can produce thermal stress; and secondly, it affects the conditions for martensitic transformation. An increase in temperature requires more energy for the phase transformation [3], and changes in martensitic formation induce a new driving force for crack growth [2, 4].

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1 Phase field model for the coupled problem

The heat transfer and constitutive equations along with PF models for fracture and martensitic transformation have been developed to simulate this coupled phenomena. The total chemical free energy is written as [1–3]:

$$\psi_{tot} = \psi_{sep} + \psi_{gr} + \psi_{loc} + \psi_{el} \tag{1}$$

$$\psi_{sep} = \int_V \left[k_s \frac{G_c}{L_c} \left(1 + \frac{A(T)}{2} c^2 - \frac{B(T)}{3} c^3 + \frac{D(T)}{4} c^4 \right) \right] dV \tag{2}$$

$$\psi_{gr} = \int_V (G_s\, L_s \, \| \nabla s \| ^{\,2} + \frac{1}{2} k_g G_c\, L_c \sum_{i=1}^{2} \| \nabla c \| ^{\,2}) dV, \quad \psi_{loc} = \int_V \frac{G_s}{4 L_s} (1-s)^2 dV \tag{3}$$

$$\psi_{el} = \int_V \left[\frac{K(c)}{2} tr^{-} (\varepsilon^{el})^2 + \ (s^2 + \eta) \left(\frac{K(c)}{2} tr^{+} (\varepsilon^{el})^2 + \mu(c) (e^{el}) : (e^{el}) \right) \right] dV \tag{4}$$

$$\varepsilon^{el}(u, c, T) = \varepsilon - \varepsilon^{pt}(c) - \varepsilon^{th}(T) \tag{5}$$

Finally the problem will be solved by implementing the following main equations simultaneously.

$$\nabla \sigma = 0, \quad \rho c_{th} \dot{T} + (s^2 + \eta) \kappa \nabla^2 T = 0, \quad \frac{\partial c}{\partial t} = -M_c \frac{\partial \psi_{tot}}{\partial c}, \quad \frac{\partial s}{\partial t} = -M_s \frac{\partial \psi_{tot}}{\partial s} \tag{6}$$

2 Numerical implementation and results

The following numerical simulation is conducted in two dimensions. The geometry, boudary conditions, material properties and numerical parameters are shown in Fig. 1. In this simulation, the evolution of martensitic microstructure, fracture behavior and temperature are obtained (see Fig. 2) by solving the governing Eqs. 6 using the finite element method for time and space under plane strain conditions. As can be seen from the results, the phase transformation from austenite to martensite starts at the crack tip, which is more difficult to appear in the higher temperature areas. According to the formed martensitic structure, the crack tends to propagate at the boundaries between austenite and martensite.

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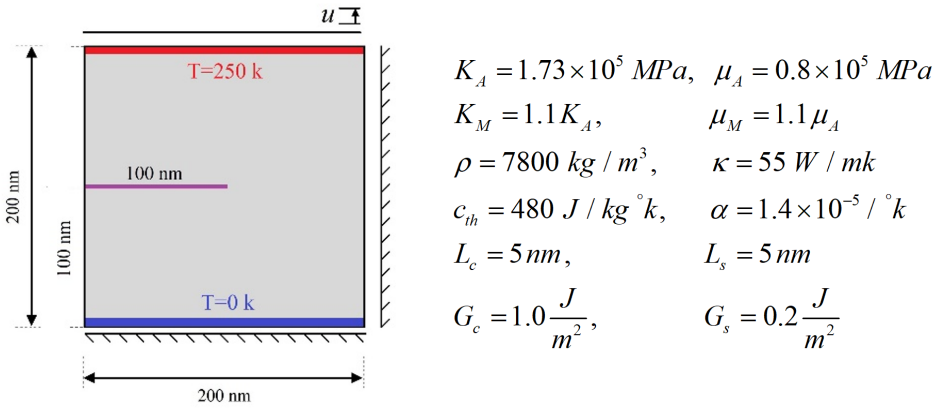

Fig. 1: Geometry, boundary conditions and initial crack position [1, 3].

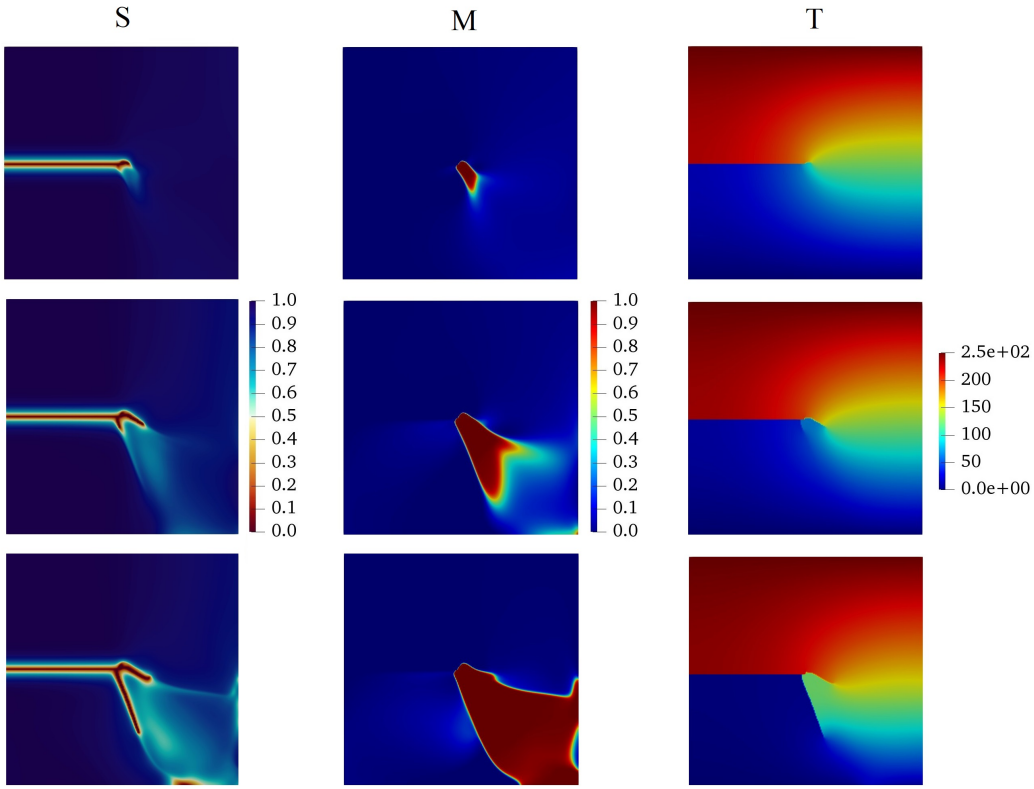

Fig. 2: Evolution of the crack field (S), martensitic variant (M) and temperature (T).

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