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A phase field approach to study of transformation induced micro–cracking in a martensitic phase transformation

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In this study, a coupled phase field (PF) method for the simulation of crack propagation and martensitic phase transformations is developed. In order to investigate the crack field and martensitic microstructure evolution the concept of the thermodynamic driving force, interfacial energy, the elastic energy, and the kinetic of phase field equations are introduced (time dependent Ginzburg Landau equation) [1]. The weak form and an algorithm for the solution of corresponding equations are implemented in the finite element program (FEAP). Since the phase transformation can form during the application of high amount of stresses, the influence of microcrack propagation on the formation of the martensitic phase has been studied. The crack tip produces high amount of concentrated stresses, which lead to a change in the distribution of the martensitic phases and it can also deviate the crack direction [2].

1 A combined phase field approach

The PF models for the martensitic transformation and crack propagation are combined together to simulate the two coupled physical processes. The total free energy is written as [3, 4]:

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

$$\psi_{ch} = \int_V \left[k_s \frac{G_c}{L_c} f(c_1, c_2) + \frac{1}{2} k_g G_c \, L_c \sum_{i=1}^{2} \|\nabla c_i\|^2 \right] dV \tag{2}$$

$$f(c_1, c_2) = 1 + \frac{A}{2}\left(c_1^2 + c_2^2\right) - \frac{B}{3}\left(c_1^3 + c_2^3\right) + \frac{C}{4}\left(c_1^2 + c_2^2\right)^2 \tag{3}$$

$$\psi_{gr} = \int_V G_s \, L_s \, \|\nabla s\|^2 dV, \qquad \psi_{loc} = \int_V \frac{G_s}{4L_s}(1-s)^2 dV \tag{4}$$

$$\psi_{el} = \int_V \left[\frac{K(c)}{2} tr^-(\varepsilon - \varepsilon^{pt}(c_i))^2 + \ (s^2+\eta)\left(\frac{K(c)}{2} tr^+(\varepsilon - \varepsilon^{pt}(c_i))^2 + \mu(c)(e - e^{pt}) : (e - e^{pt}) \right) \right] dV \tag{5}$$

The time dependent Ginzburg Landau (TDGL) equations have been written as:

$$\frac{\partial c_i}{\partial t} = -M_c \frac{\partial \psi_{tot}}{\partial c_i}, \quad \frac{\partial s}{\partial t} = -M_s \frac{\partial \psi_{tot}}{\partial s} \tag{6}$$

2 Numerical implementation and results

The geometry, material properties and the eigenstrains are shown in Fig. 1 [4, 5]. In this study, two simulations have been investigated to observe the behavior of the crack and the phase transformation. In the first model the fracture is coupled with the first variant of martensite (see Fig. 2) while in the second example the effect of the second variant has been considered (see Fig. 3) . The models have been simulated into a four-node quadrilateral plane element with bilinear shape functions.

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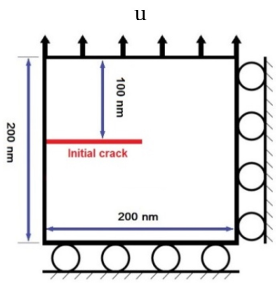

$$K_A = 102.7\ GPa, \qquad \mu_A = 28\ GPa,$$
$$K_M = 1.1 K_A, \qquad \mu_M = 1.1 \mu_A$$
$$\varepsilon^{pt}(c_1) = [0, 0,\ 0.1], \quad \varepsilon^{pt}(c_2) = [0, 0, -0.1]$$

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

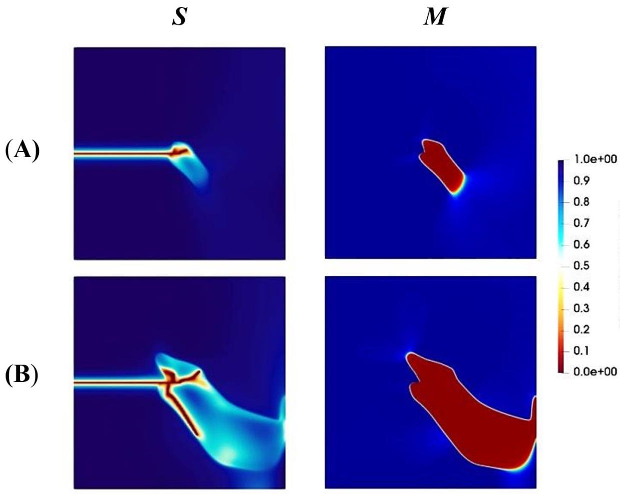

Fig. 2: Evolution of the crack field (S) and martensitic variant (M) by considering one variant of martensite. Rows (A) and (B) correspond to times 6 μs, and 36 μs.

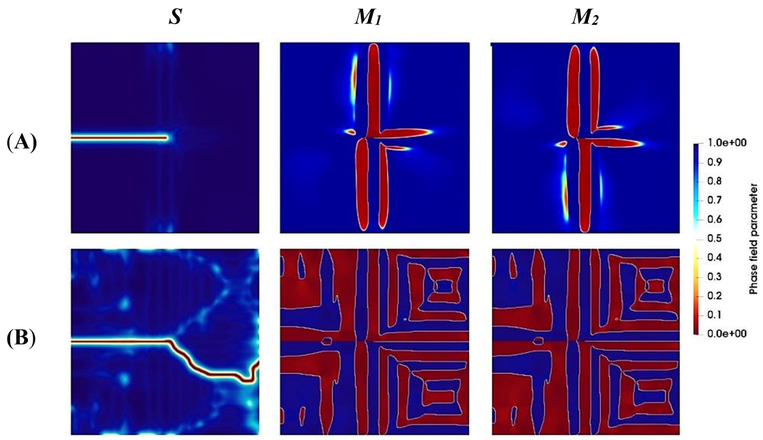

Fig. 3: Evolution of the crack field (S) and martensitic variants (M1, M2) by considering two variants of martensite. Rows (A) and (B) correspond to times 4 μs, and 45 μs.

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