LATENT HEAT EFFECT ON THE MICROSTRUCTURES OF SINGLE CRYSTAL SHAPE MEMORY ALLOYS

Chen Xuan[*a)], Cheng Peng[**], Yan Yan[*] & Yongzhong Huo[*]
[*]*Department of Mechanics and Engineering Science, Fudan University ,Shanghai, 200433, China*
[**]*Department of Mechanical Engineering and Materials Science, Rice University, Houston, TA 77005, US*

Summary Evolutions of microstructures and temperature fields are obtained experimentally for Cu-based single crystalline shape memory alloys under uniaxial tension tests of various loading rates and theoretically for quasi-static and dynamical equations of displacements and temperatures. It was found that the latent heat release can have a large effect on the characteristics of the microstructures and temperatures of the stress induced martensitic process under dynamical loadings.

INTRODUCTION

Fine layered microstructures with parallel bands are often observed during the stress-induced martensitic transformation (SiMT) of shape memory alloys (SMAs). Latent heat effect for dynamical SiMT is strongly related to loading rates and requires more detailed studies due to its importance in most applications. Variational models based on nonconvex elastic energy have been successfully used to predict the characteristics of equilibrium microstructures. Due to the mathematical and computational difficulties, the most complete understanding was gained in one-dimensional (1D) approximations [1,2]. In this report, latent heat effect to SiMT is studied both experimentally and theoretically. In experiments of CuAlNi single crystalline SMAs, the evolutions of microstructures and temperature fields were recorded together with the stress-strain hysteresis for various uniaxial loading rates. 1D variational model was used to study the strain rate effect. For quasi-static loading, the Euler-Lagrange (E-L) equation of minimization is solved by using the homotopy analysis method (HAM)[3], which provides both the bifurcation analysis and the approximated series solutions. For dynamical process, the temperature equation is solved together with the coupled displacement equations by using finite difference method (FDM). The results are compared with experiments.

EXPERIMANTALS AND 1D MODEL

Experimentals

Tensile specimens of CuAlNi (Cu-13.19Al-4.43Ni (wt %)) SMA single crystal were tested at room temperature (T_0=296 K) in stagnant air on standard testing machines with applied stretching rates (nominal strain rates) of 10^{-4} -10^{-1} /s. The surface morphology was recorded by an imaging camera and the surface temperatures by four thermal couples attached on the back side surface, uniformly along the loading direction. Thus, the evolution of microstructures and the temperature fields are detected experimentally together with the stress-strain curves.

1D models

The energy functional for 1D SMAs in the elastic foundation model[1,2] is $F=\int_0^L [W(u_x)+\alpha u_{xx}^2+\beta(u-u_H)^2]dx$ with $W(u_x)$ a nonconvex elastic energy. α and β are positive constants for the strain gradient interfacial energy and inhomogeneity. $u(x)$ is the displacement and $u_H=(u(L)-u(0))x/L+u(0)$ the homogeneous displacement. The corresponding governing equation reads

$$\rho u_{tt}=W(u_x,T)_{u_xu_x}u_{xx}-2\alpha u_{xxxx}-2\beta(u-u_{\mathrm{H}}),\ \text{and}\ \ c_pT_t=\kappa T_{xx}-c(T-T_e)\ +ATu_{xt} \qquad (1)$$

For quasi-static loading, the left term in the first equation and the temperature equation need not be considered. A simple potential function[2] $W(u_x)=E(u_x^2-1)^2/4$ is used to obtain analytical solutions of the reduced E-L equation by HAM[3]. For dynamical process, we used the following energy function[4] and the coupled equations (1) are solved by FDM

$$W(u_x,T)=(K+AT)u_x+E(u_x^4-2u_x^3+u_x^2)/2-c_pT\log T/T_e+c_pT \qquad (2)$$

RESULTS AND DISCUSSIONS

HAM based quasi-static series solutions with multiple interfaces and bifurcation

It is found by using HAM that the reduced E-L equation for quasi-static process with the quartic potential will have non-trivial solutions $u\neq u_H$, only when the magnitude of the total strain $d=(u(L)-u(0))/L$ is smaller than some critical values d_c which is determined by the constants $\bar{\alpha}=\alpha/E$ and $\bar{\beta}=\beta/E$. When $-d_c<d<d_c$, several

a) Corresponding author. Email: 10210290005@fudan.edu.cn.

nontrivial solutions can exist with different interface numbers k in the range, $k_m(d) \le k \le k_M(d)$ as shown in Fig. 1a). For any (d, k) in the region, approximated analytical series solutions can be obtained. An example of such a solution is given below for an interface number $k=5$ at $d=0$ with $\bar{\alpha}=0.00015, \bar{\beta}=15$.

$$\begin{aligned} u(x) &= 7.14491\times10^{-2} sin(5x) - 5.32939\times10^{-3} sin(15x) + 9.23094\times10^{-4} sin(25x) - 1.81045\times10^{-64} sin(35x) \\ &+3.62481\times10^{-5} sin(45x) - 7.09452\times10^{-6} sin(55x) + 1.32475\times10^{-6} sin(65x) + ... \end{aligned} \quad (2)$$

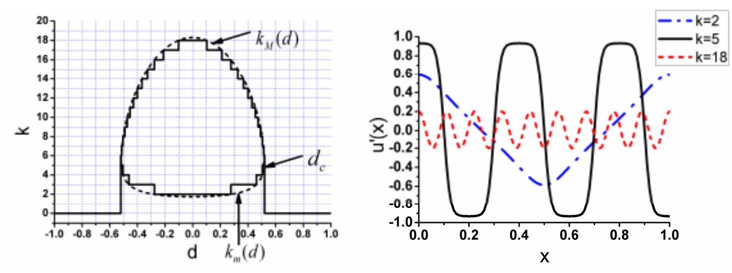

Fig. 1. HAM results: a) bifurcation diagram, b) 3 strain fields at $d=0$.

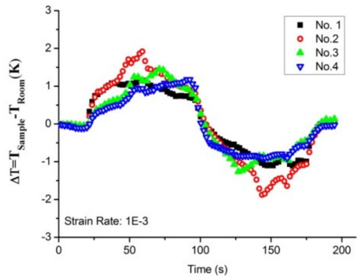

Fig. 2. Temperatures by experiments

Thus, d_c is the bifurcation point and the region shown in Fig. 1a) is the phase transition region in which some microstructures can appear. Fig. 1b) depicts three possible ones at $d=0$. The experimental observed microstructures might be the ones selected by energy minimizations[1,2] for static loadings or through kinetics for dynamical process as will be considered below.

Temperature variation and microstructures for dynamical process

In dynamical tests, the temperature of the sample varies both in time and space (Fig. 2) due to the latent heat release and absorption of SiMT. The microstructures, in particularly the interface numbers increased rather strongly with the strain rate[5] (Fig. 3). FDM simulation of (1) shows similar behaviors for the temperature fields (Fig. 4b). Thus, the latent heat effect is obvious for non-static SiMT, while it almost has little effect on quasi-static loading, and it can be rather important in the thermal and mechanical fatigue life of SMA devices.

FDM simulation of (1) (Fig. 4a), in some sense, explains the multiple solutions for the microstructures in the static solutions. At both the beginning and ending of the transformation, the number of interfaces is generally a value bigger than one, as also indicated in experiments and the HAM static solution above. The interface number during the transition process varies with time corresponding to the multiple solutions with different interface numbers in the static case.

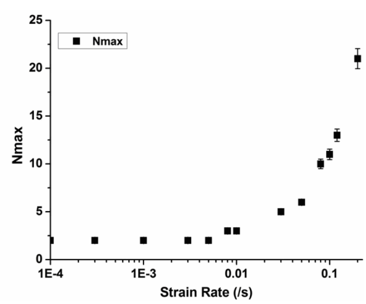

Fig. 3. Interface numbers by experiments

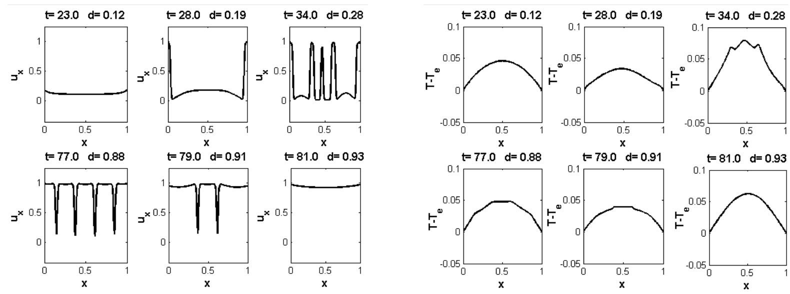

Fig. 4. FDM results: a) strains; b) temperatures

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References

[1] Huo Y., Muller I.: Interfacial and inhomogeneity penalties in phase transitions. *Continuum Mech. Therm.* **15**:395–407, 2003.

[2] Vainchtein A., Healey T. J.: Rosakis P., Bifurcation and metastability in a new one-dimensional model for martensitic phase transitions. *Comput. Methods Appl. Mech. Engrg.* **170**:407–421, 1999.

[3] Liao S. J.: Beyond Perturbation: Introduction to the homotopy analysis method, Chapman & Hall/ CRC, Boca Raton, 2003.

[4] Ngan S. C., Truskinovsky L.: Thermal trapping and kinetics of martensitic phase boundaries. *Journal of the Mechanics and Physics of Solids*, **47**:141–172, 1999.

[5] Yan Y. , Yin H. , Sun Q. P.: Huo Y., *Continuum Mech. Therm.* Accepted for publications