TEMPERATURE OSCILLATION UNDER CYCLIC PHASE TRANSITION OF NITI SHAPE MEMORY ALLOY

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Summary This paper reports the experimental phenomenon of temperature oscillation under cyclic phase transition of Polycrystalline NiTi shape memory alloy. The distinctive temperature oscillation is due to the latent heat and hysteresis heat. We elucidate the multi-scaled nature of the temporal evolution of thermal field and emphasize the important roles of time scales in the thermal response of the material.

Superelastic shape memory alloys (SMAs), when subjected to displacement-controlled cyclic deformation with strain range from 0% to 6%, exhibit distinctive temperature and stress oscillations [1]. In this paper, we report the phenomenon of temperature oscillation under cyclic phase transition. The amplitudes of the oscillations vary significantly with the deformation frequency and the number of cycles and can even damage the material and affect its performance before the oscillations reach steady-state. This paper investigates the effects of the deformation frequency on the cyclic response of a superelastic NiTi polycrystalline wire (3.5mm diameter and 40mm gage length) by measurement of temperature over frequency range of 0.0004~1 Hz in stagnant air (lumped characteristic relaxation time=55s) with ultra-thin thermocouple (0.025mm diameter with relaxation time 0.05s).

EXPERIMENTAL RESULTS

Six typical experiment results were shown in figure 1. It is observed that, for all the test frequencies, steady-state cyclic thermal responses of the specimen can be reached after a number of transient loading cycles, exhibiting a kind of "thermal shake down". The number required to reach the steady-state cycle (N_s) linearly increases with the loading frequency (f), but the time required to reach the steady-state cycle (t_s) are almost constant (around 110s) for all frequencies. With the increase in the number of cycles in given cyclic deformation, the average temperature of the wire remain almost unchanged at lower frequency (Fig. 1a), shifted down (soften) at intermediated frequency (Fig. 1b to Fig. 1d) and shifted up (harden) at higher frequency (Fig. 1e and Fig. 1f). This is the results of the competition between the two time scales (loading time $t_p/2$ (for heat release) and relaxation time $\overline{t_h}$ (for heat transfer)).

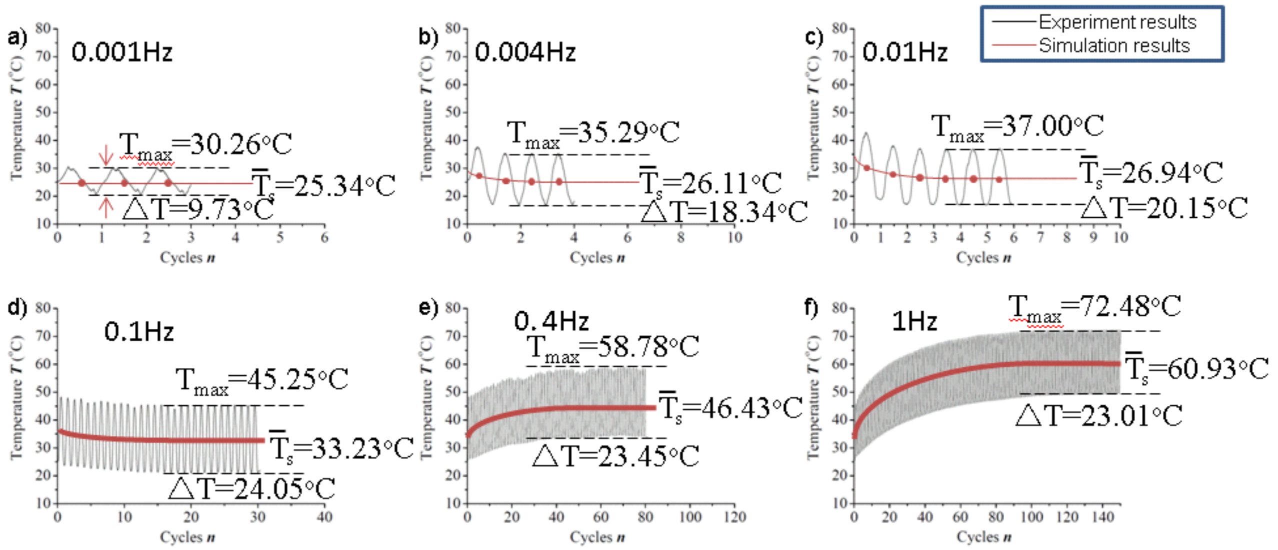

Fig. 1 Temperature evolution for different frequencies

At the lower frequency, since the heat transfer via convection and conduction is much faster than the heat generation, the thermal effect on the cyclic response is quite weak and the temperature oscillation in the steady-state cycle (stable stage) is almost the same as that of the first cycle. At the intermediate frequency (for example 0.01Hz), heat release rate is comparable to the heat transfer rate. Then, the thermal effect becomes strong, leading to non-isothermal and oscillating features in the cyclic thermal behaviors. The temperature oscillation becomes 20.2°C and the average temperature per

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cycle of the specimen was higher than the room temperature. The average temperature reduced by 5~6^{o}C in the transient stage and eventually reached its steady-state value 26.9^{o}C. For the cyclic tests of 1 Hz, the thermal effect on the cyclic behavior became even more significant. On the one hand, the release/absorption of latent heat caused a near instantaneous temperature increase/decrease in the specimen with an amplitude of 23^{o}C in temperature oscillation. On the other hand, the released hysteresis (mechanical dissipative) heat from the intrinsic hysteresis loop of the material had not enough time to transfer out (because $t_p << t_h$) and accumulated rapidly in the specimen, causing a large increase in the average temperature (per cycle) to the saturation value of 60.9^{o}C, and the peak value of the temperature increases from 46.5^{o}C (in the first cycle) to 72.5^{o}C (in the steady-state cycles). The steady-state average temperature increased rapidly with the frequency and has no saturation at high frequency (Fig. 2a). The steady state temperature oscillation increased with frequency and becomes saturated when the frequency is larger than 0.01Hz (Fig. 2b).

ANALYSIS AND DISCUSSION

To have a quantitative understanding of the roles of the time scale of loading (or the rate of latent heat release and heat accumulation) and the time scale of heat transfer, modeling and analysis on the physical process were performed. The model solution can characterizes both the transient and steady-state temperature oscillation under different frequencies and ambient conditions. The temperature history $T(t)$ of a NiTi SMA wire under displacement controlled sinusoidal cyclic deformation of frequency $f\,(=1/t_p)$ was obtained by solving the lumped 1D heat transfer equation of the wire as:

$$T(t)=T_0+\frac{D_0\bar{t}_h\omega}{2\pi\lambda}+\left(\frac{l_0\bar{t}_h^{\,2}\omega^2}{2\lambda(1+\bar{t}_h^{\,2}\omega^2)}-\frac{2D_0\bar{t}_h^{\,3}\omega^3}{\pi\lambda(1+4\bar{t}_h^{\,2}\omega^2)}\right)e^{-\frac{t}{\bar{t}_h}}+\frac{l_0\bar{t}_h\omega}{2\lambda\sqrt{1+\bar{t}_h^{\,2}\omega^2}}\sin\left(\omega t-\cos^{-1}\frac{1}{\sqrt{1+\bar{t}_h^{\,2}\omega^2}}\right)-\frac{D_0\bar{t}_h\omega}{2\pi\lambda\sqrt{1+4\bar{t}_h^{\,2}\omega^2}}\sin\left(2\omega t+\sin^{-1}\frac{1}{\sqrt{1+4\bar{t}_h^{\,2}\omega^2}}\right)$$

In which, T_0 is the initial temperature at $t=0$, ω is the angular velocity $(\omega=2\pi f)$, $\bar{t}_h(=r\lambda/\bar{h})$is the lumped characteristic relaxation time of the heat convection, l_0 is the latent heat, λ is heat capacity, D_0 is the isothermal stress hysteresis loop area (intrinsic mechanical dissipative heat). The first two terms on the right side of the equation define the mean temperature of the specimen in steady state cycle. It is caused by the accumulation of the intrinsic hysteretic heat of the phase transition. The third term describes the transient stage average temperature and exponentially decays to zero. The last two terms are the temperature oscillations caused by latent heat and hysteresis heat, respectively. It is further shown that such frequency-dependent oscillations of temperature originate from the competition between the time scale of reversible phase transition process (which is accompanied by the generation of hysteresis heat and the release/absorption of latent heat) and the time scale of heat transfer with the ambient. From the equation, we can clearly see that, in addition to the material properties and parameters, the ratio of the two time scales $\bar{t}_h\cdot\omega$ determines the average temperature and the temperature oscillation. This prediction of the model agrees well with the experimental data (Fig. 2).

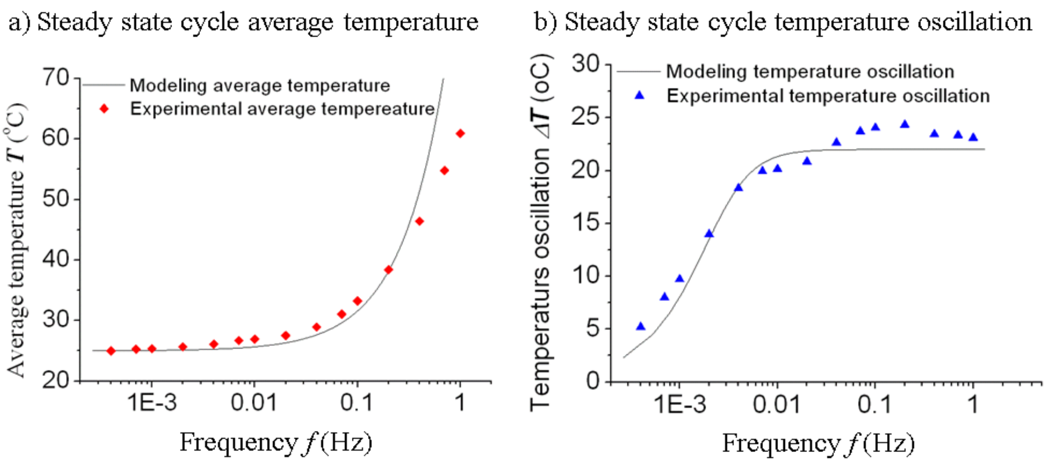

Fig. 2 a) Steady state cycle average temperature and b) Steady state cycle temperature oscillation

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