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Kinetics of the reverse martensitic transformation in shape memory alloys under an abrupt heating pulse

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ABSTRACT

The kinetics of the reverse martensitic transformation in shape memory alloy wires is studied under conditions at which it is restricted neither by the rate of heat transfer nor by mechanical inertia. Two characteristic times for the transformation are identified and estimated. A model provides a universal expression that fits all experimental measurements performed at different temperatures. The kinetic law predicted by the model indicates that interface velocities are governed by viscous resistance and are thus much slower than the shear wave speed, even under very large driving force values.

Martensitic and reverse martensitic phase transformations are considered to be "very fast", even supersonic [1,2], due to their diffusionless and athermal nature [3,4]. However, how fast they really are has yet to be resolved. To uncover the true kinetics of the phase transformation, experiments have to be performed under conditions at which the transformation rate is restricted neither by the rate of heat transfer nor by mechanical inertia. For example, in cases where the phase transformation is induced by temperature change, the rate of heating or cooling has to be much faster than the rate of the phase transformation. Previous studies did not meet this condition (see discussion in refs. [5,6].). In addition, the inherent strain associated with the martensitic phase transformation results in motion of the phase transforming body and attached structures (masses). When a fast martensitic transformation is induced, accelerations associated with this motion result in large forces that may determine the overall mechanical response and hinder the kinetics of the phase transformation.

Studies of the stress induced martensitic transformation in shape memory alloys (SMA) using mechanical impact at high strain rates have reported that the phase transformation is almost completed within <100 μs [7–9]. A study of phase front propagation by an assembly of strain gauges mounted along a NiTi specimen demonstrated velocities in the range of 37–370 m/s [9]. However, no clear correlation between the phase front velocity and the driving force was observed and the kinetic law of the phase transformation has not been uncovered.

Recently, our group developed a unique experimental method in which a detwinned SMA wire is heated by an electric pulse with a peak of 10^5–10^6 W and overall duration of <5 μs [5,6]. The experimental results demonstrate stress levels approximately 2 GPa and elastic strain rates of approximately $10^3\ s^{-1}$ [6]. This attainment indicates the potential of harnessing this actuation concept in applications that require a one-directional fast and powerful motion. However, the rate of the mechanical response in these experiments was influenced by the inertia of a mass, which was attached to the end of the wire [6]. As a result, the previous study [6] did not uncover the true kinetics of the phase transformation.

In this paper, we employ the same concept of rapid heating, as in refs. [5,6], but use a modified experimental setup, in which the SMA wire is fixed at both ends, such that there are no moving masses, except for local motions of the wire itself. Under these conditions, the rate of the phase transformation is restricted neither by heat transfer nor by the kinematics of the experimental setup. Dedicated force sensors with a bandwidth of 350 kHz and a response time of approximately 1 μs (see details in ref. [6]) are attached to both ends of the SMA wire and allow measurement of the mechanical response associated directly with the phase transformation. Analysis of the experimental results leads to the identification of two characteristic times, in the microsecond scale, which reflect the true kinetics of the phase transformation and are related to material properties. Moreover, we suggest a kinetic law and a model for the phase transformation that provides a normalized stress vs. time representation that is valid for experiments performed under different temperature jumps and wire lengths.

The average temperature of the wire as a function of time t can be expressed by

$$T(t) = T_R + \frac{U_{in}(t)}{C_p} - \frac{H \cdot x(t)}{C_p} - \frac{Q(t)}{C_p}, \tag{1}$$

where T_R is the room temperature. The second term represents the temperature rise due to the Joule heating, where C_p is the heat capacitance

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of NiTi and $U_{in}(t)$ is the input electric energy per unit volume of the NiTi wires. The third term represents the temperature reduction due to the latent heat H of the phase transformation, where $x(t)$ is the volume fraction of the austenite and $\frac{H}{C_p} = 29$ °C [10]. Note that C_p of the martensite and austenite phases is approximately the same [10] and therefore H is approximately constant as a function of temperature. In the last term, Q is the wasted heat that is transferred from the wire to its surrounding.

Measurements of the current and voltage directly on the SMA wire showed that the input energy $U_{in}(t)$ has a characteristic time of approximately 1 μs and 99.3% of the energy is provided during 5 μs [6]. As will be shown later, the two characteristic times that describe the evolution of $x(t)$ are in the range of 20–30 μs, i.e. much larger than the characteristic time of the temperature rise. Therefore, practically, the phase transformation occurs after the heating pulse is ended. The characteristic time of Q is on the order of 1 s and therefore this term is negligible. As will be shown later, due to the developed stresses the phase transformation is not completed and in most tests $x \le 0.2$. As a result, the third term in Eq. (1) is smaller than 6 °C and therefore the temperature is approximately constant during the phase transformation. Throughout the paper we report estimations of the temperature immediately after the electric pulse, i.e., when the third and fourth terms in Eq. (1) are negligible. The temperature estimations are based on a value of $C_p = 0.837$ J/(g·°K) [10]. Previous high rate infrared photography showed that after the end of the heating pulse, the temperature along the wire is uniform [6].

All tests presented in this letter have been performed on Dynalloy's Flexinol 90 °C ® NiTi wires ($A_F \approx 80$–90 °C) with diameters of 0.2 and 0.38 mm. Before and after each pulse test, the bottom end of the wire was released from its fixture and a small mass of 53 g was hanged on it. Then, the wire was heated slowly by gradually increasing a DC current and the motion of the mass was monitored by a laser displacement sensor (MTI-2125H). When the martensite to austenite phase transformation was completed, the mass stopped moving and the wire's length was measured. This procedure allowed us to measure the plastic strain accumulated during the test and the initial pre-elongation strain $\varepsilon_0 \cong 0.035$ of the martensite [6]. It was found that in all tests the plastic strain was smaller by an order of magnitude than $x\varepsilon_0$.

Fig. 1 shows typical force vs. time curves measured by the two force sensors during the same test. Both curves exhibit the same behavior, which is explained herein. The time $t = 0$ is defined by the onset of the electrical pulse. Prior to this time, the wire is stretched and held at a predefined stress σ_0 (250 MPa in this test). At time $t = 0$ there is an artificial sharp burst of force readings that is induced by the electric pulse and lasts approximately 10 μs. After the disturbance disappears, the force readings return to approximately the initial value of σ_0 and stay at this level for a 'dead' time of 20–30 μs, marked as t_{dead} in Fig. 1. The duration of the electric pulse is much shorter than the dead time

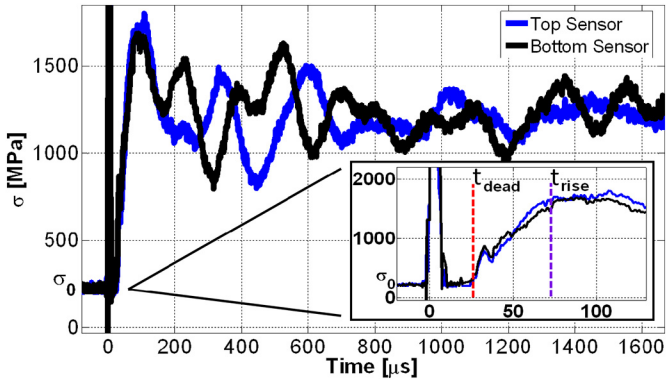

Fig. 1. Stress recorded at both ends of the SMA wire. The inset shows zoom-in on the beginning of the test.

and therefore during most of the dead time the wire's temperature is above the transition temperature A_F. Nevertheless, there is no observable change in the stress. Note that ordinary thermal expansion is negligible in this type of experiments. The strain due to this effect is smaller than 10^{-3} and is related to a reduction of the stress by <70 MPa, which is comparable to the noise level of the force sensors.

The dead time may contain contributions from the time that it takes for the longitudinal stress waves to travel along the wire Δt_{Wire} and along the connector that connects the wire and the force sensor $\Delta t_{Instrument}$. The observation that the two force sensors measure an indentical value of t_{dead} (see the inset in Fig. 1) up to a temporal resolution of $\delta t_{dead} = 1$ μs, indicates that at the macro (mm) scale the wire responds homogeneously and therefore Δt_{Wire} is negligible. This result is in agreement with IR images reported in ref. [6], which show no observable localization of the phase transformation. We used short alumina connectors that provide $\Delta t_{Instrument} = 4$ μs [6], i.e., much smaller than t_{dead}. This means that the dead time originates primarily from the relatively slow rate of the phase transformation in this time interval.

We define an incubation time, which describes a characteristic time of the phase transformation, by $t_0 = t_{dead} - \Delta t_{Instrument}$. Measurements taken from eight wires with different lengths in the range of 13–120 mm showed that each wire exhibits a different value for t_{dead}, but there is no correlation between t_{dead} and the wire length. This observation provides another indication that Δt_{Wire} is negligible. Calculation of the incubation times showed that its average value is $t_0 = 22$ μs and the standard deviation is 4 μs.

At $t = t_{dead}$, the stress starts increasing rapidly until it reaches a maximum at $t_{dead} + t_{rise}$. This observation indicates on a transition from slow to fast rate of the phase transformation that occurs at $t = t_0$. The source for this transition is still unknown. It may be related to a transition from nucleation controlled to propagation controlled phase transformation. Another option is a transition from small austenite islands, on the scale of one or few grains (grain size of Flexinol is about 100 nm [11]), to large austenite regions that contain numerous grains.

During the interval $t_{dead} < t < t_{dead} + t_{rise}$, the elastic strain rate is approximately 10^3 s^{-1} [6]. After the first stress peak, the force vibrates around a plateau value until the vibrations dampen and the stress settles at an equilibrium value: σ_{eq}. Measurements at longer time scales show that the stress remains constant at σ_{eq} for several seconds and returns to approximately σ_0 when the wire cools down.

In our previous study [6] we showed by high rate photography that string-like vibrations of the SMA wire are excited by the rapid stress rise before the first stress peak. Moreover, a clear correlation between the wire curvature due to the string-like vibration and the maxima and minima of the force vibrations, including the first stress peak, has been directly visualized. The force vibrations are not fully harmonic but can still be characterized by a time period T_{vib}. Due to the string-like vibrations, the stress along the wire is not uniform, as is manifested by the difference between the temporary readings of the two force sensors. Nevertheless, the two curves in Fig. 1 exhibit the same values of t_{dead}, t_{rise}, T_{vib}, and σ_{eq} and differ only in the temporary phase of the force vibration.

Fig. 2a shows the results of a set of tests, taken using the same wire, but subjected to different input energies and in accordance different temperature jumps. It is observed that t_0 is weakly dependent on the temperature and t_{rise} seem to be temperature independent. In the following, we present a model that explains the temperature independence of t_{rise}. The main assumption of the model is that during the fast stage of the phase transformation (i.e., at $t > t_{dead}$) the kinetics follows a linear law of the form

$$dx/dt = \mu g. \tag{2}$$

Here x is the volume fraction of the austenite phase, g is the thermodynamic driving force for the phase transformation and μ is a mobility