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Martensitic inelasticity of TiNi-shape memory alloy under pulsed loading

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Abstract

Some inelastic properties of TiNi shape memory alloy in martensitic state under pulsed loading were investigated. Two millimeter-diameter TiNi wire specimens were subjected to deformation by a magneto-pulsing installation under three-point bending conditions. The dependencies of residual strain on the force amplitude applied to the strikers during eight test series using different mechanical pulse durations from 400 to 1300 μs, were obtained. For each test series the threshold (minimal) value of force impulse amplitude which causes appearance of residual strain was found. Also, the threshold value of stress in each case was calculated using the elastic beam method, the value found to be within the range of 300–900 MPa. In order to describe dynamic mechanical behavior of TiNi shape memory alloy in martensitic state an attempt was made to apply the principles of yielding based on the concept of the so called incubation time. For inelastic deformation the incubation time was calculated based on the data resulting from the above-mentioned experiments. Its value of about 2 ms characterizes the range of occurrence of dynamic properties.

Keywords: TiNi shape memory alloy; Magneto-pulsing installation; Pulse loading; Dynamic behavior; Threshold stresses; Incubation time criterion

1. Introduction

Mechanical and functional properties of TiNi have evoked considerable interest in the last decades, especially the properties appearing at dynamic loading [1–10]. As for the case of slow loading, mechanical parameters of the mechanisms of deformation have been thoroughly studied. It is known that when in martensitic state at the initial stage of inelastic straining the main deformation mechanisms of martensite are twinning and reorientation. Such kind of deformation is reversible during heating. At the first stages of inelastic straining dislocation mechanisms are also involved. This kind of deformation is irreversible. However, up to the present time little knowledge has been what the mechanical parameters of these mechanisms are at short pulse loading, nor has the characteristic time of each process been investigated. To describe mechanical behavior of shape memory alloys in martensitic state we suggest using the theory of yielding and fracture based on the "incubation time" concept [11]. To determine the parameters of this theory we should determine the critical amplitudes of force leading to inelastic strain of TiNi in martensitic state and calculate the characteristic time of this process. For this purpose magnetic pulse loading [12,13] was used. This method allows controlling the amplitude of electric impulse and its duration. For the purposes of further investigation this inelastic strain could be divided into residual and recovery parts, obtaining the values of critical forces for each part.

2. Theoretical

To study inelastic behavior of shape memory alloys in martensitic state we propose to use the following criterion [11]

$$\frac{1}{\tau}\int_{t-\tau}^{t}\left(\frac{\sigma(s)}{\sigma_{\mathrm{Y}}}\right)^{\alpha}\mathrm{d}s < 1, \tag{1}$$

where τ is the incubation time of yielding, σ_{Y} the threshold stress in quasi-static test, α the dimensionless shape parameter and $\sigma(t)$ is applied stress (zero for $t<0$). The Eq. (1) provides a sufficient condition of persistence of elastic state. The moment of transition to inelastic state corresponds to the earliest violation of this condition. A similar criterion proved to be effective for analysis of yielding of common metals [14].

Now we mention some advantages of the criterion (1). It is applicable for an arbitrary law of the stress-time dependence. For example, criterion (1) can explain both the growth of yield limit in tests with constant strain-rate, and "yield delay" in tests with constant value of the stress applied. These criteria are valid for an arbitrary duration of loading (no matter long or short).

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The behavior of the material is described using a limited set of constants that can be determined experimentally.

It immediately follows from Eq. (1) that at threshold loads the transition to inelastic state occurs if

$$\max_t \left(\frac{1}{\tau}\int_{t-\tau}^{t}\left(\frac{\sigma(s)}{\sigma_Y}\right)^{\alpha} \mathrm{d}s\right) = 1. \tag{2}$$

It will be shown below that in our case the stress-time dependence can be approximated by

$$\sigma(t) = A\sin\left(\frac{\pi t}{D}\right), \tag{3}$$

where A is the stress amplitude and D is mechanical pulse duration. For the given material characteristics σ_Y, α, and τ and for Eq. (3), the dependence of a threshold amplitude on pulse duration can be calculated. For given D we determine the minimal value of A to satisfy Eq. (2). The result is as follows:

$$A = \sigma_Y\left(\frac{1}{\mu}\cdot I\left(\alpha, \min\left\{\mu, \frac{\pi}{2}\right\}\right)\right)^{-\frac{1}{\alpha}} \quad \text{where}$$

$$\mu = \frac{\pi\tau}{2D} \quad \text{and} \quad I(\alpha,\mu) = \int_0^{\mu} (\cos(z))^{\alpha}\,\mathrm{d}z. \tag{4}$$

For example if $\alpha = 1$ then

$$A = \begin{cases} \mu\sigma_Y, & \mu \ge \dfrac{\pi}{2} \\ \dfrac{\mu\sigma_Y}{\sin\mu}, & \mu < \dfrac{\pi}{2} \end{cases}.$$

It is evident that for a very long pulse ($D \gg \tau$) we have $A \underset{\mu\to 0}{\longrightarrow} \sigma_Y$ thus the quasi-static criterion is valid.

3. Experimental

Experimental investigations have been carried out at the Research Center of Dynamics (St. Petersburg State University and the Institute for Problems of Mechanical Engineering of the RAS). The object of investigations were wire specimens 2 mm in diameter made of equiatomic TiNi alloy, annealed at 500 °C during 1 h ($M_f = 36.5\,^{\circ}$C). At room temperature they were in fully martensitic state. Dynamic tests were carried out at room temperature using magneto-pulse installation [12,13] with energy content of up to 15 kJ. This installation allows generating pressure impulses of microsecond durations and amplitudes of up to 2 GPa. A special technique based on the three-point bending test of a wire specimen has been elaborated. A pressure pulse was passed from a copper bus (1) to the specimen (3) through a triangle steel striker (2) (Fig. 1). The characteristics of electro-magnetic pulse were controllable to a high degree of accuracy. The change of amplitude and the duration of the electro-magnetic pulse, as well as the change of the striker mass and the distance between the supports in the range of 26–49 mm were used to vary the amplitude and duration of mechanical impulse acting to the specimen. The process of loading consisted of two stages. At the first stage, acceleration of striker occurs while the deflection of the specimen is very small. During the second stage, the pressure of the bus on the striker is zero; hence the response of the specimen depends only on kinetic energy of the striker. The pressure transmitted from the bus to the striker could be approximated by the following:

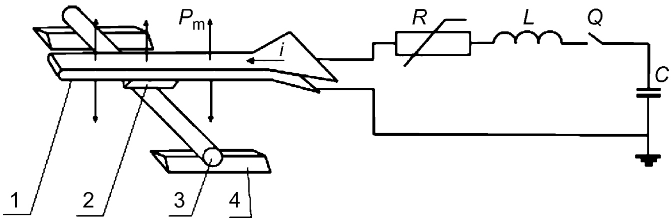

Fig. 1. Scheme of magneto-pulse installation and scheme of loading: P_m: pressure initiated by magnetic field, i: current, C: capacity, Q: switchboard, R: formative vylite resistor, L own inductance of pulse current generator. (1) Output bus, (2) striker, (3) investigated sample; (4) supports.

$$P(t) = \begin{cases} P_{\max}\sin^2\dfrac{\pi t}{T}, & 0 \le t \le T \\ 0, & t > T \end{cases}, \tag{5}$$

where duration of electro-magnetic pulse T was several microseconds. Force amplitude was defined by the following formula

$$F = S\max_t P(t) = P_{\max}S,$$

where S is the contact area of the bus and the striker.

4. Results and discussion

In each test series the residual deflection and force amplitude were measured (the results of one test series with constant pulse duration are presented in Fig. 2). In each series, the critical force F_{CR} was determined by extrapolation to the zero deflection. The dynamic bending tests were accompanied by standard quasi-static bending tests. The critical force F_{CR} in this case was 10 N. It should be noted that the values of F_{CR} obtained in the dynamic test are 3 orders higher than those displayed in case of quasi-

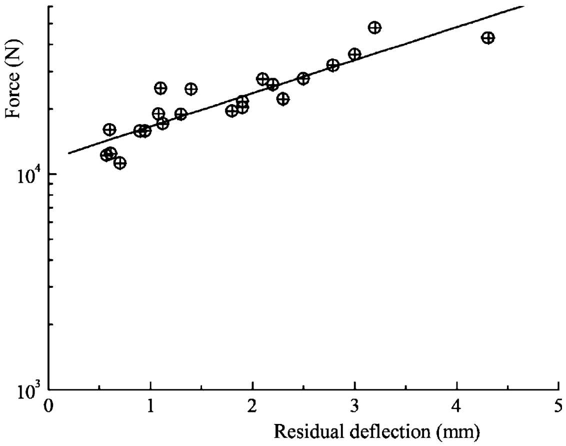

Fig. 2. Residual deflection of TiNi wire specimens versus amplitude of force applied to the striker. Electromagnetic pulse duration 3.5 μs, distance between supports 30 mm, striker mass 5.5 g (mechanical pulse duration 700 μs).