TORSIONAL DEFORMATION AND ROTARY DRIVING CHARACTERISTICS OF SMA THIN STRIP

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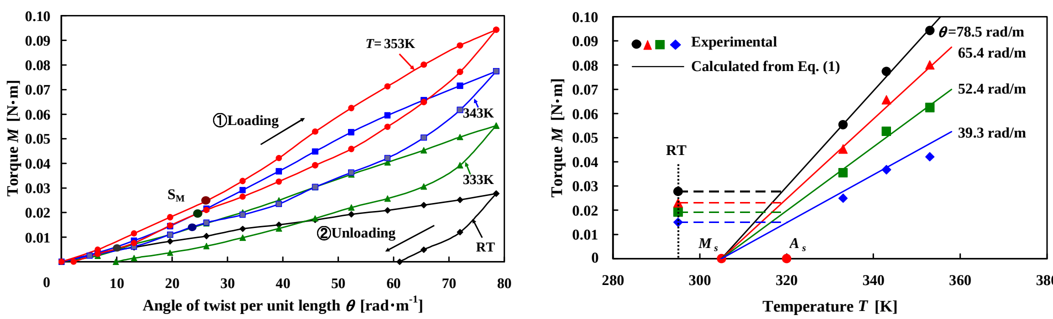
1. Introduction

Shape-memory alloys (SMAs) have played a leading part in research into smart materials. The main characteristics of SMAs are the shape memory effect (SME) and superelasticity (SE). Using the torsional deformation of a TiNi SMA tube, twist in the blades of rotor aircraft was investigated in order to improve the flight performance. In practical applications making use of SMA thin strips, torsional deformation can be obtained simply by gripping both ends without any mechanical process. In the present study, the torsional deformation properties of a TiNi SMA thin strip are investigated. The characteristics of energy storage, dissipated work and fatigue are also investigated.

2. Relationship between torque and angle of twist

The relationship between torque M and angle of twist per unit length θ for the heat-treated material as obtained from the torsion test is shown in Fig.1.As can be seen from Fig.1(a), M increases with an increase in θ. At room temperature, a large residual angle of twist per unit length appears after unloading, giving evidence of the SME. At T = 333K, since T is $A_s < T < A_f$ and therefore there is a partial effect of superelasticity in which the reverse transformation does not completely occur, a residual angle of twist appears after unloading. At temperatures above 343K, the angle of twist recovers during unloading and no residual angle of twist appears. As can be seen from the relationship between torque and temperature in the loading process, shown in Fig.1(b), torque M increases in proportion to temperature rise T-M_s for the same angle of twist per unit length θ at temperatures above A_s. The slope increases in proportion to θ.

I shall next discuss the relationship between torque M and angle of twist ϕ based on the evidence of the elastic deformation due to torsion. In the case of torsion in a bar of rectangular cross-section of width w and thickness t, the angle of twist per unit length θ is express by using modulus of rigidity G.



(a) Relation between torque and angle of twist.

(b) Relation between torque and temperature in the loading process.

Fig.1. Results of torsion test for heat-treated material.

Considering the fact that the M-θ and M-$(T$-$M_s)$ curves in the loading process are close to straight lines, the relation becomes

$$M = awt^3 G\theta(T - M_s) \tag{1}$$

where the factor a depends on the ratio w/t. The values of G at temperatures above and below A_s differ in a ratio of about 3 : 1. By taking the average value G = 20GPa and $a = 1.61 \times 10^{-2}\mathrm{K}^{-1}$, the calculated results can be found as shown by the solid lines in Fig.1(b).

3. Energy storage and dissipation

The area under the loading curve of the relation between the torque and the angle of twist corresponds to work done during loading. The area under the unloading curve corresponds to the recoverable strain energy E_r. The area inside the hysteresis loop during loading and unloading corresponds to the dissipated work W_d.

The relations between E_r and W_d and temperature T at $\theta = 78.5\mathrm{rad{\cdot}m^{-1}}$ (total angle of twist $\phi = \pi$) for the heat-treated materials are shown in Fig.2. As can be seen, E_r increases markedly in proportion to T as the torque during unloading increases with increasing temperature. The relation between E_r and T is expressed by a linear equation: E_r=$b(T$-$A_s)$ for b=3.68mJ$\cdot$K^{-1}, where A_s denotes the reverse transformation starting temperature under no stress and A_s=295K.

On the other hand, as can be seen in Fig.2, the dissipated work W_d decreases gradually with an increase in temperature T. The rate of decrease in W_d is small and W_d is only slightly dependent on T.

4. Torsion fatigue properties

The relations between amplitude of the twisting angle per unit length θ_a and the number of cycles to failure N_f for the as-received and heat-treated materials obtained from the torsion fatigue test are shown in Fig.3, expressed on a logarithmic scale.

As can be seen in Fig.3, the number of cycles to failure N_f decreases with an increase in the amplitude of the twisting angle per unit length θ_a. This relation is approximated by a straight line on the logarithmic graph. The fatigue life curve in the region of low-cycle fatigue seems therefore to be expressible in an equation similar to that already obtained for the fatigue life curve of TiNi SMA wires under bending. This can be seen in Eq.(2)

$$\theta_a \cdot N_f^{\ \beta} = \alpha \quad \text{for} \quad \begin{cases} \beta = 0.20, \alpha = 580\,\mathrm{rad \cdot m^{-1}} : \text{Heat - treated} \\ \beta = 0.15, \alpha = 280\,\mathrm{rad \cdot m^{-1}} : \text{As - received} \end{cases} \tag{2}$$

where α and β represent θ_a where N_f = 1 and the slope of the logθ_a-logN_f curve, respectively. The calculated results obtained from Eq.(2) are shown by solid lines in Fig.3.

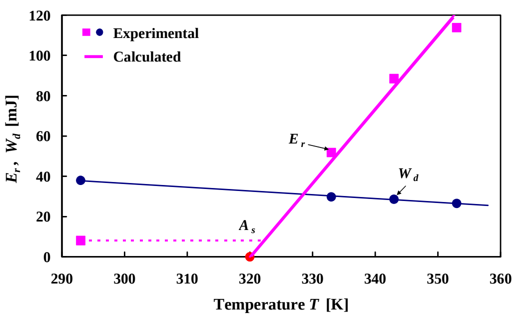


Fig.2. Dependence of E_r and W_d on temperature at $\theta = 78.5\mathrm{rad{\cdot}m^{-1}}$ ($\phi = \pi$) for heat-treated material

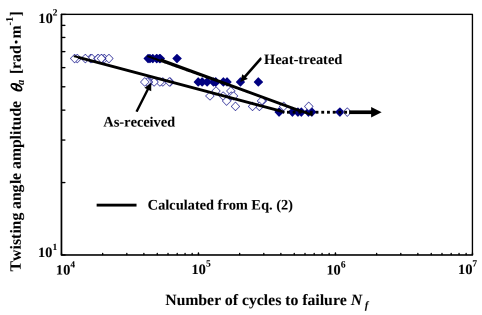


Fig.3. Fatigue life curves of SMA thin strip for torsion.