Transactions of the Materials Research Society of Japan 29[7] 3053-3056 (2004)

Fatigue Properties of Highelastic Thin Wire and Superelastic Thin Tube of NiTi Alloy

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The tensile deformation and rotating-bending fatigue properties of a highelastic thin wire and a superelastic thin tube of NiTi alloy were investigated experimentally. The results obtained are summarized as follows. (1) The stress-strain curve of the highelastic thin wire is approximately straight till strain of 4% with stress of 1400 MPa and depends little on temperature. (2) Modulus of elasticity of both the wire and tube is low, having superior performance of flexibility which is necessary for medical application. (3) The strain-based fatigue curve of the alloy consists of two straight lines. The strain amplitude of fatigue limit is in the region of 0.6~0.8%. (4) In the tube, the fatigue crack initiates on the inner surface since the inner surface is rough, resulting in short fatigue life.

Key words: Superelasticity, Highelasticity, Nickel-Titanium Alloy, Thin Tube, Thin Wire, Fatigue

1. INTRODUCTION

In a shape memory alloy (SMA), the shape memory effect appears mainly due to the martensitic transformation (MT) [1-3]. Since a NiTi alloy is superior for cyclic deformation property, fatigue strength and corrosion resistance in SMAs, it is most widely used. The MT appears according to variation in temperature and stress. The stress-induced martensitic transformation (SIMT) strain of several percents diminishes according to the reverse transformation. The reverse transformation appears by heating in the case of shape memory effect or by unloading in the case of superelasticity (SE).

In order to apply SE to a medical catheter tube, a thin-walled small diameter tube was developed recently. On the other hand, if SE is applied to a medical guidewire, it is expected from the view point of torque transmitting ability that the straightness of the stress-strain curve is kept till the range of large strain and the width of the hysteresis loop is narrow. In order to achieve this requirement, a highelastic wire with very narrow width of the hysteresis loop was developed. In particular, the high stiffness and high pushability in compression is necessary for the guidewire. For this purpose, high yield stress is necessary. Since the guidewire and the catheter tube are subjected to cyclic deformation in medical applications, the deformation properties which prescribe the functional performance, in particular, the fatigue properties are important in order to evaluate the reliability of SMA elements.

In the present paper, the tensile deformation and fatigue properties of a newly developed highelastic thin wire and a SE thin tube of NiTi alloys are investigated. By performing rotating-bending fatigue tests in air and in water, the influence of temperature on the fatigue life is investigated.

2. EXPERIMENTAL METHOD

2.1 Materials and specimen

The materials tested were two kinds of rectilinear NiTi alloys produced by Furukawa Electric Co. A highelastic thin wire (FHP-NT), 0.5 mm in diameter, and a SE thin-walled small diameter tube (NT-Tube), 0.9 mm in external diameter and 0.7 mm in internal diameter, were used.

2.2 Experimental apparatus

In the tension test, an SMA property testing machine composed of a tension machine and a heating-cooling device was used [4].

In the fatigue test, a rotating-bending fatigue machine was used [5].

2.3 Experimental conditions

Tension tests were carried out in air under various ambient temperatures T.

Rotating-bending fatigue tests were carried out in air and in water. In the test in air, temperature was room temperature (RT). In the test in water, frequency f was 500 cpm and temperatures T were 303 K, 333 K and 353 K.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Deformation properties of highelastic thin wire

Tensile deformation property: The stress-strain curves for FHP-NT, obtained from the tension test under various temperatures T are shown in Fig. 1. As can be seen in the figure, the stress-strain curves of FHP-NT are close to a straight line till strain of 4 % and stress of 1400 MPa, and the width of the hysteresis loop under loading and unloading is very narrow. Modulus of elasticity is 55 GPa which is smaller than that for stainless steel of 190 GPa. FHP-NT shows high flexibility. Residual

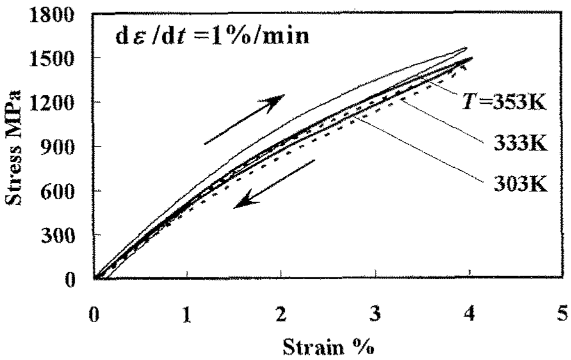


Fig. 1 Stress-strain curves for FHP-NT

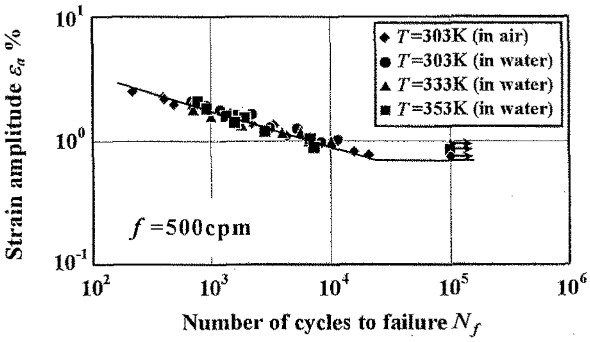


Fig. 2 Relationship between strain amplitude and number of cycles to failure for FHP-NT

strain after unloading is small. From these results, it is ascertained that FHP-NT has excellent performance of flexibility, high yield stress and straightness which is necessary for application to a medical guidewire.

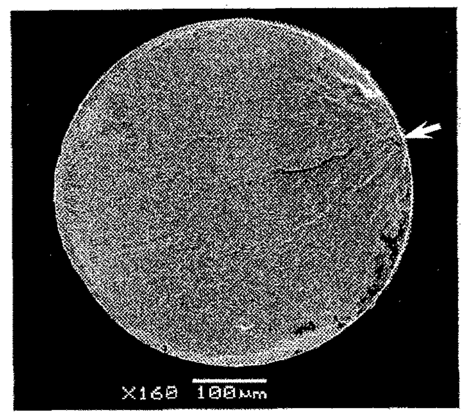
On the other hand, as can be seen in Fig. 1, the difference of the stress-strain curves is small under various temperatures. Therefore the dependence of the stress-strain curve on temperature is slight, and the almost constant deformation property can be obtained.

Bending fatigue property: The relationships between strain amplitude ε_a and the number of cycles to failure N_f for FHP-NT, obtained from the fatigue tests at various temperatures T in water are shown in Fig. 2. In Fig. 2, the points with an arrow denote the case where failure did not occur. As can be seen in these figures, the strain-life curves display changes of direction. The knee of the strain-life curve is in the region of N_f around 2×10^4 cycles and ε_a = 0.6 % ~ 0.8 %. The fatigue life increases in the high-cycle fatigue side beyond the knee.

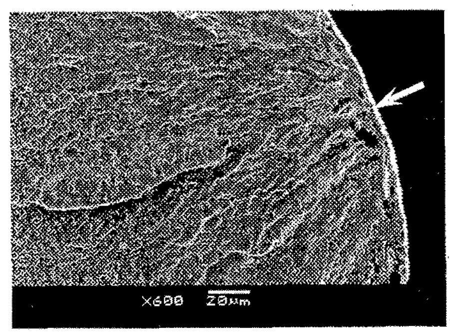
As can be seen in Fig. 2, the difference of fatigue life does not clearly appear under various temperatures. Since the stress-strain relationship for FHP-NT does not depend on temperature, the influence of temperature on the fatigue life does not appear.

The SEM photographs of fracture surface for FHP-NT in the case of T = 303 K, f = 500 cpm and ε_a = 0.94 % are shown in Fig. 3. The whole fracture surface, the fracture surface at crack initiation and the fracture surface in unstable fracture are shown in Figs. 3(a), 3(b) and 3(c), respectively.

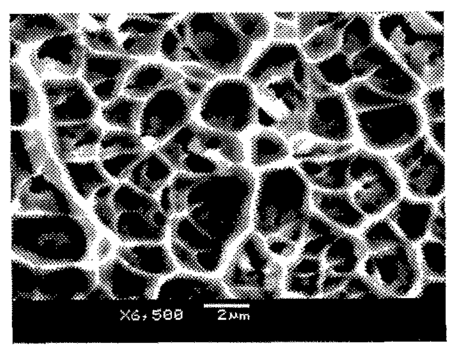
As can be seen in Figs. 3(a) and 3(b), the crack nucleates at a certain point on the surface of the wire and propagates toward the central part with the radial river



(a) Whole fracture surface



(b) Fracture surface at crack initiation



(c) Fracture surface at unstable fracture

Fig. 3 SEM photographs of fracture surface for FHP-NT

pattern. Although small cracks are observed on the whole surface of the wire, only one crack grows preferentially. Following the fatigue fracture with a fan-shaped surface, unstable fracture occurs finally. As can be seen in Fig. 3(c), isometric dimples with an average diameter of about 2 μm appear in the region of unstable fracture.

3.2 Deformation properties of superelastic thin tube

Tensile deformation property: The stress-strain curves for NT-Tube, obtained from the tension test at various temperatures T are shown in Fig. 4. As can be seen in the figure, NT-Tube shows the SE property. The MT stress is about 200 MPa at 303 K. An overshoot does not occur at the MT starting point. Modulus of elasticity is 55 GPa. Therefore it is ascertained that NT-Tube is superior for flexibility which is necessary for application to a medical catheter tube.

Bending fatigue property: The relationships between strain amplitude ε_a and the number of cycles to failure N_f for NT-Tube, obtained from the fatigue tests at various temperatures T in water are shown in Fig. 5. In Fig. 5, the points with an arrow denote the case where failure did not occur. As can be seen in the figure, the strain-life curve displays changes of direction. The knee of the strain-life curve is in the region of N_f = (5 ~10)×10^4 cycles and ε_a = 0.5 % ~ 0.7 %.

As can be seen in Fig. 5, the fatigue life of NT-Tube scatters compared with that of FHP-NT. As can be seen in Fig. 5, the overall fatigue life becomes shorter in proportion to temperature. Since the MT stress increases in proportion to temperature, the higher the temperature, the shorter the fatigue life.

The relationships between strain amplitude ε_a and the number of cycles to failure N_f for a superelastic thin wire (SE-NT) and NT-Tube, obtained from the fatigue test at room temperature under f = 500 cpm in air, are shown together in Fig. 6. As can be seen in this figure, though the MT stress of NT-Tube is lower than that of SE-NT, the fatigue life of NT-Tube is shorter. The difference of fatigue life between the thin wire SE-NT and the thin tube NT-Tube can be explained as follows. In the case of the thin wire SE-NT subjected to bending, the central part in the cross-section is elastic region. The fatigue crack initiates on the surface of the wire and propagates radially toward the central part. Since stress is low in the elastic region of the central part in the cross-section, crack propagation will be suppressed. On the other hand, in the case of thin tube NT-Tube, the MT stress is almost constant in the stress plateau as already observed in Fig. 4, and therefore the SIMT appears as far as on the inner surface of the thin tube in the region of strain amplitude for low-cycle fatigue. Since the elastic region of the central part in the cross-section does not exist in the thin tube, crack propagation will not be suppressed. Therefore, after crack initiates on the inner surface of the tube and penetrates to the outer surface, two crack fronts will propagate to great extent toward both circumferential directions in the thin-walled cross-section. In the result, though the MT stress is low in NT-Tube, the fatigue life is short.

The cause that the fatigue crack initiates on the inner surface and the fatigue life scatters is due to roughness on the inner surface of NT-Tube. In the forming process of the tube, the inside of the tube is not constrained and therefore the inner surface is rough. Ten point height of roughness profile is 3.4 μm on the outer surface and 11.2 μm on the inner surface. Since the inner surface is rough, local stress concentration occurs in the elements of the inner surface and therefore the fatigue crack will initiate easily. In the result, the fatigue crack initiates on the inner surface and the fatigue life scatters. In order to improve the scattering of the fatigue life for NT-Tube smaller and to make the fatigue life longer, the development of the forming method to make roughness on the inner surface of the thin tube smaller is the future subject.

The SEM photographs of fracture surface for NT-Tube in the case of T = 303 K, f = 500 cpm and ε_a = 2.3 % are shown in Fig. 7. The whole fracture surface, the fracture surface at crack initiation, the fracture surface in unstable fracture and the fracture surface at final rupture are shown in Figs. 7(a), 7(b), 7(c) and 7(d), respectively.

As can be seen in Fig. 7, fatigue crack initiates on the inner surface of the tube. The positions of crack initiation are distributed at several points with the width of 50 μm in the circumferential direction. The crack propagates toward the outer surface with the river pattern. When the circumferential length of the crack which has penetrated the wall of the tube becomes almost equal to wall-thickness of 100 μm, the final unstable fracture occurs. In the region of unstable fracture, the crack fronts in both sides propagate in the circumferential direction in the cross-section. In this region, dimples with average diameter of about 4 μm are arranged in the

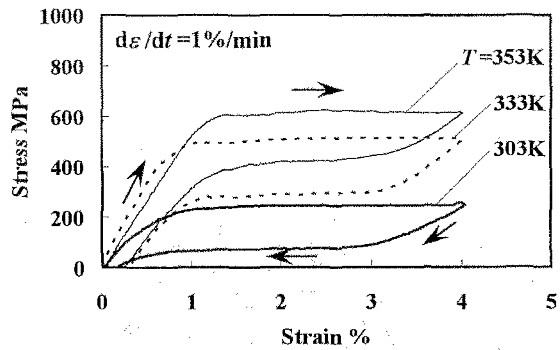


Fig. 4 Stress-strain curves for NT-Tube at various temperatures T

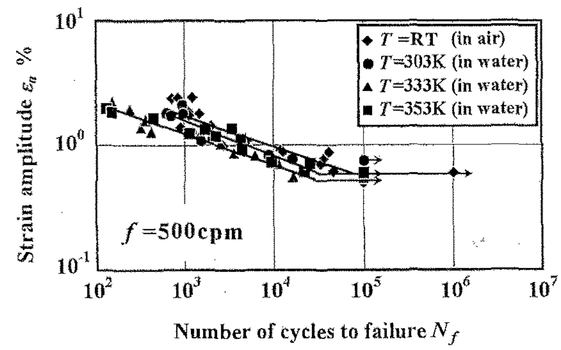


Fig. 5 Relationship between strain amplitude and number of cycles to failure for NT-Tube

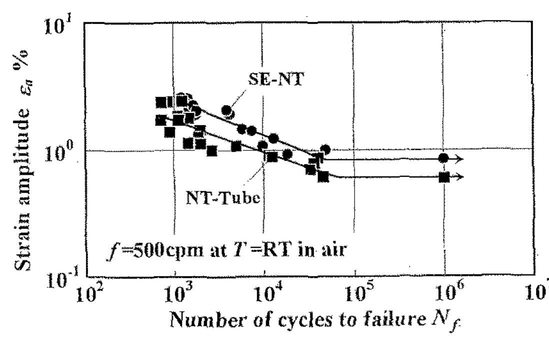
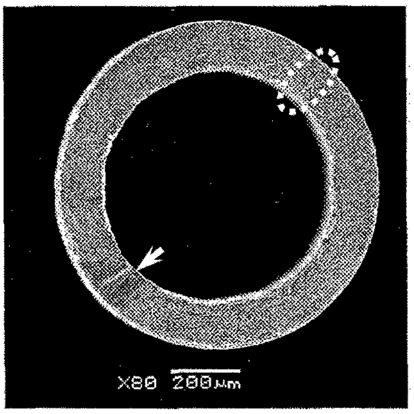
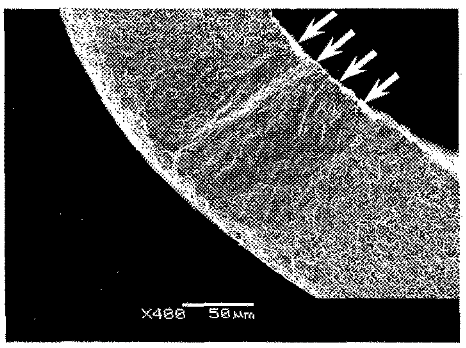


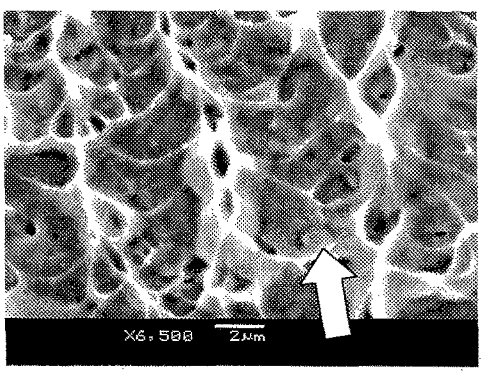
Fig. 6 Relationship between strain amplitude ε_a and number of cycles to failure N_f for SE-NT and NT-Tube



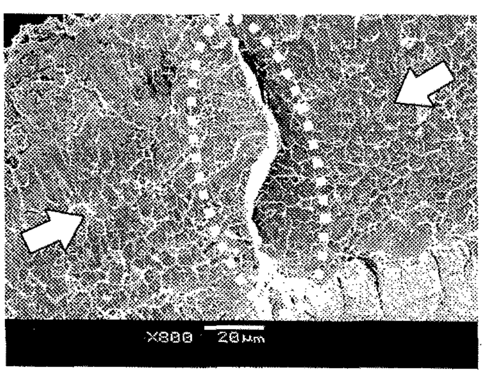
(a) Whole fracture surface



(b) Fracture surface at crack initiation



(c) Fracture surface at unstable fracture



(d) Fracture surface at final rupture

Fig. 7 SEM photographs of fracture surface for NT-Tube

circumferential direction corresponding to the propagation of the crack. The final rupture part is located in the opposite side of the crack initiation. In the final rupture part, two crack fronts join, and a small step or a ratchet mark is observed.

4. CONCLUSIONS

The basic tensile deformation and rotating-bending fatigue properties for the highelastic thin wire FHP-NT and the superelastic thin tube NT-Tube of NiTi alloys were investigated experimentally. The results obtained are summarized as follows.

(1) The stress-strain curve for FHP-NT is almost straight till strain of 4 % and stress of 1400 MPa, and the width of hysteresis loop is very narrow. The stress-strain curve does not depend on temperature. Modulus of elasticity is 55 GPa which is smaller than that of 190 GPa for stainless steel. Therefore FHP-NT has excellent performance of flexibility and highelasticity which is necessary for a medical guidewire.
(2) The fatigue life for FHP-NT does not depend on temperature.
(3) The stress-strain curves for NT-Tube shows large hysteresis loop under loading and unloading. The MT stress increases in proportion to temperature. Modulus of elasticity and the MT stress for NT-Tube are low, and therefore NT-Tube is superior for flexibility which is necessary for a medical catheter.
(4) The strain-fatigue life curves for each alloy display changes of direction. The strain amplitude of fatigue limit, corresponding to the knee of the strain-life curve for FHP-NT, is in the region of 0.6 % ~0.8 %. The strain amplitude of fatigue limit for NT-Tube is lower than that for FHP-NT by 0.1 %.
(5) The fatigue life for NT-Tube is shorter and has larger scattering compared to that of a superelastic thin wire. This occurs due to the fact that the inner surface of NT-Tube is rough and the fatigue crack initiates on the inner surface. In order to improve the fatigue life for NT-Tube longer and scattering smaller, the development of the forming method to make surface roughness of the inner surface smaller is the future subject.

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(Received October 10, 2003; Accepted March 20, 2004)