Fatigue Properties of the Ti–Ni Base Shape Memory Alloy Wire

Youngsik Kim

Department of Mechanical & Materials Engineering, Korea Maritime University,
Yeongdo-ku, Dongsam-dong, 606-791, Pusan, Korea

The effect of the alloy compositions on the cyclic bending fatigue behaviors of the Ti–Ni base shape memory alloy wires was investigated using a rotary bending fatigue tester specially designed for wires. The fatigue test results were discussed in connection with the static tensile properties. The results were summarized as follows. (1) The martensite inducing stress increased with the increasing of the Ni-content. (2) The fatigue life decreased with the increasing of the test temperature and the Ni-content. (3) The fracture pattern resulted from the rotary bending fatigue test has changed from the dimple pattern under the room temperature and small cyclic strain to the quasi-cleavage fracture under the high temperature and large cyclic strain.

(Received December 17, 2001; Accepted May 14, 2002)

Keywords: martensitic inducing stress. cyclic strain amplitude. fatigue life curve. quasi-cleavage fracture

1. Introduction

The Ti–Ni alloys subjected to cyclic deformation change their deformation behavior, causing for degradation of characteristic functions such as shape memory effect and superelasticity, and finally leads to failure.^{1,2)} Therefore, it is practically very important to understand the fatigue characteristics of the Ti–Ni alloys in order to utilize these functions in various types of applications.

Several papers have been reported so far on the fatigue properties of the Ti–Ni alloys with the shapes of plate and bar.^{3–5)} However, the data on the Ti–Ni shape memory alloy wires that are used in most applications such as the fields of sensor, actuator, or medicine are scarcely available except a few for the present.^{6,7)} In the case of wires, the cyclic bending deformation mode is very important, because components made of the shape memory wires receive cyclic bending or twisting in many applications.

The unique characteristics of Ti–50.9 at%Ni shape memory alloy wire under the cyclic bending deformation mode were clarified in the previous work by the authors.⁸⁾ And S. Miyazaki *et al.* investigated the characteristics of the fatigue life of Ti–50 at%Ni and Ti–40Ni–10Cu(at%) shape memory alloy wires.⁹⁾

However, there is yet uncertainty concerning the effect of the variations of the Ni-content in the Ti–Ni base shape memory alloy wires.

The present work was intended to find out how the Ni-content affects the deformation behavior and the fatigue lives at the various test temperature for Ti–Ni base shape memory alloy wires.

2. Experimental Details

The experimental materials were 3 kinds of Ti–Ni base shape memory alloy wires with the compositions of Ti–50.0 at%Ni, Ti–50.5 at%Ni and 50.85 at%Ni, respectively. The diameter of the wires was 1.0 mm. The wires were cut to 100 mm length for rotary bending fatigue tests and 40 mm length for tensile tests. The specimens were annealed at

673 K for 3.6 ks followed by water quenching. After the heat-treatment, they were polished lightly by emery papers to remove lightly oxidized surface layer, then electropolished. The transformation temperature of the specimens was measured by DSC (Differential Scanning Calorimeter). Table 1 shows the A_s and A_f temperature of each specimen.

For investigating the characteristics of the static deformation behaviors, the tensile tests were first conducted using an Instron 4469 Model with a heating silicon oil chamber. Fatigue tests were carried out using a rotary bending fatigue tester which is specially designed for wires in previous work.⁸⁾

The cyclic speed was kept constant at 6.7 Hz and the test temperature changed from 293 to 383 K with an interval of 30 K. After the fatigue tests, fracture surfaces were investigated by the scanning electron microscope in order to clarify the fracture mode.

3. Results and Discussion

In case of Ti–Ni base shape memory alloys, the deformations accompany the R-phase (Rhombohedral phase) transition and the subsequent martensitic transformation depending on the thermo-mechanical treatment and Ni-content.¹⁰⁾ Figure 1 shows stress-strain curve at 353 K for Ti–50.5 at%Ni alloy.

This curve shows 4 turning points. The points ① and ② are analyzed to be associated with the R-phase transition, ③ with the martensitic transformation start and ④ with the permanent deformation start. Figure 2 shows stress-strain curves at various test temperatures for Ti–50.5 at%Ni alloy wire. With increasing test temperature, the stress (σ_M) for inducing marten-

Table 1 A_s and A_f temperature of the specimens.

Ti–Ni alloys	Temperature (K)	
	A_s	A_f
Ti–50.0 at%Ni	335.8	360.8
Ti–50.5 at%Ni	329.5	358.4
Ti–50.85 at%Ni	310.5	333.5

Fig. 1 The stress-strain curve of the Ti-50.5 at%Ni alloy at 353 K.

Fig. 2 The stress-strain curve of the Ti-50.5 at%Ni alloy.

Fig. 3 The stress-strain curve at 323 K.

sitic transformation increases. Moreover, superelastic strain that is the strain to permanent deformation start increases with increasing test temperature.

Figure 3 shows the comparison of the stress-strain curves for 3 different alloy compositions at 323 K. With increasing the Ni-content of the alloy, the σ_M and superelastic strain increases.

The strain (ϵ_M) for inducing martensitic transformation and the strain (ϵ_R) for inducing R-phase appear as shown in Fig. 4 from the stress-strain curves of Fig. 3. Figure 4 shows that the ϵ_R and ϵ_M are almost constant at all test temperatures.

Fig. 4 ϵ_M - ϵ_R as function of temperature.

Fig. 5 ϵ_a - N_f curves in the Ti-50.5 at%Ni alloy.

Fig. 6 ϵ_a - N_f curves at 323 K.

Fatigue tests were conducted at the four temperatures at which the stress-strain curves were measured. The relationship between strain amplitude (ϵ_a) and fatigue life (N_f , the number of rotary-bending cycles) of the Ti-50.5 at%Ni alloy is shown in Fig. 5. Four ϵ_a - N_f curves are shown and each of them consists of three straight line. The reason why the ϵ_a - N_f curves have the three region is thought to be caused by occurring of the deformation mode change at the points of ϵ_M and ϵ_R . Those results are similar to previous works by

Fig. 7 Fractographs of the Ti–50.85 at%Ni alloy.

authors and by S. Miyazaki, *et al.*^{8,9)} In the highest strain amplitude and intermediate strain amplitude regions, the fatigue life increases with decreasing test temperature. However, the fatigue life is almost the same irrespective of test temperature in the lowest strain amplitude region. The ε_M and ε_R are also shown by dashed lines in Fig. 5. These strains correspond to the two inflection points in each ε_a - N_f curve. The temperature dependence of the fatigue life in the highest and intermediate strain amplitude regions is caused by the increasing of the σ_M with the test temperature as shown in Fig. 2. The insensitivity to the test temperature in the lowest strain amplitude is due to the full elastic deformation mode in this range.

The effects of the Ni-content on the fatigue life were investigated through the ε_a - N_f curves of the three alloys with different Ni-content. Figure 6 shows ε_a - N_f curves of the three alloys with different Ni-content at 323 K. The fatigue life decreases with increasing of the Ni-content in the highest and intermediate strain amplitude. This result comes from the increasing of the σ_M with the Ni-content under same strain amplitude in this range as shown in Fig. 3. The narrow gap among the alloys in the lowest strain amplitude is due to the elastic deformation mode in this range in all alloys.

The fracture modes were investigated through the observation of the fracture surfaces using the SEM. Figure 7 shows the comparison of the micrographs of the fractured surfaces under various loading conditions for Ti–50.85 at%Ni alloy.

Under same test temperature, the deeper dimples and shear lip patterns are observed at lower strain amplitude as shown in (a) and (b). Moreover, under same strain amplitude, the more quasi-cleavage facets are observed at higher temperature as shown in (b) and (d). This results show that the fracture mode changes from dimple mode under room temperature and low strain amplitude to quasi-cleavage mode under high temperature and high strain amplitude.

The hardening occurs under high temperature and high strain as shown in Fig 2. The quasi-cleavage mode under high temperature and high strain amplitude is thought to be caused by this hardening.

4. Conclusions

The static deformation and rotary bending fatigue properties of the Ti–50.0 at%Ni, Ti–50.5 at%Ni and Ti–50.85 at%Ni alloy wires were investigated at various test temperature. Main results are summarized as follows:

(1) The stresses (σ_M) for inducing martensitic transformation increased with increasing of the Ni-content while the strain (ε_M) for inducing martensitic transformation are hardly affected by the Ni-content.

(2) The relationship between strain amplitude (ε_a) and fatigue life (N_f) consisted of three straight lines with two turning points. In the highest strain amplitude and intermediate

strain amplitude, the fatigue life decreased with increasing of the test temperature and Ni-content. However, the fatigue lives were hardly affected by the test temperature and Ni-content in the lowest strain amplitude where specimens deform elastically.

(3) The rotary bending fatigue fracture behavior of the Ti-Ni base shape memory alloy wires changed from ductile mode at room temperature and small strain amplitude to quasi-cleavage mode at high temperature and large strain amplitude.

Acknowledgments

This work was conducted as the succeeding work after the co-working with prof. S. Miyazaki, University of Tsukuba. The author is grateful to prof. S. Miyazaki for supplying the experimental materials and his cooperations.

REFERENCES

- 1) S. Miyazaki, T. Imai, Y. Igo and K. Otsuka: Metall. Trans. **A17A** (1986) 115–120.
- 2) S. Miyazaki: *Engineering Aspects of Shape Memory Alloys*, ed. by T. W. Duerig *et al.*, (Butterworth-Heinemann, 1990) 394–413.
- 3) K. N. Melton and O. Mercier: Acta Metall. **27** (1979) 137–148.
- 4) S. Miyazaki, Y. Sugaya and K. Otsuka: Proc. MRS Inter. Mtng. Adv. Mater. Tokyo, Vol. 9, MRS, (1989) 251–262.
- 5) B. Strnadel, S. Ohashi, H. Ohtsuka, S. Miyazaki and T. Ishihara: Mater. Sci. Eng. **A203** (1995) 187–196.
- 6) J. L. McNichols, Jr., P. C. Brookes and J. S. Cory: J. Appl. Phys. **52** (1981) 7442–7453.
- 7) H. Tobushi, P. H. Lin, A. Ikai, S. Yamada: Transactions of the Japan Society of Mechanical Engineering **61** (1995) 2355–2361.
- 8) Y. S. Kim and S. Miyazaki: Fatigue properties of Ti–50.9 at%Ni shape memory wires, SMST International Committee (1997) 473–478.
- 9) S. Miyazaki, K. Mizukoshi, T. Ueki, T. Sakuma and Y. Liu: Mater. Sci. Eng. **A273–275** (1999) 658–663.
- 10) S. Miyazaki and K. Otsuka: Metall. Trans. **A17A** (1986) 53–63.