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Deformation Analysis for Coil Spring of Ti-Ni Shape Memory Alloy in the Superelastic Regime

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FEM analysis results for coil spring specimens of Ti-Ni shape memory alloys were compared with experimental results in the superelastic regime. The input data for FEM analyses were obtained from wire specimens of the same material as that of coil spring specimens. The calculated results did not agree with experimental results. Two possible causes were pointed out on the disagreement between calculated and experimental results. One is the insufficient treatment in the constitutive relations under multiaxial stress states. The other is the discrepancy in the work rates between coil spring specimens and wire specimens. Some examinations were performed on these points.

Key words: shape memory alloy, titanium-nickel alloy, coil spring, superelastic behavior, FEM analysis

1. INTRODUCTION

Shape memory alloys are receiving attention in various fields. In areas such as engineering and medicine, the applications of shape memory alloys are being studied and are actually in use [1-3].

The coil springs of the Ti-Ni shape memory alloy are widely used for many applications because they can create a large deformation. However, in order to promote the further application of these springs, some improvements in the design method of them are necessary.

In the present design procedure, some coil springs are produced preliminarily to obtain the data of their deformation behavior. Then the design parameters of objective coil springs are obtained from these data. To improve such design method, it seems necessary that coil springs of shape memory alloys can be designed from the fundamental data for the wire specimens of the same material. In other words the development of the method for calculating the deformation behavior of coil springs from the data of the deformation behavior of wires of shape memory alloys is necessary.

In the present paper we show the experimentally obtained deformation data for coil springs of Ti-Ni shape memory alloys in the superelastic regime. We also show the results of the FEM calculations for the deformation of coil springs using the deformation data for wire specimens of the same material, and discuss about the results in comparing FEM calculations and experimental results for coil springs

2. EXPERIMENT

2.1 Specimen

The specimens were coil springs made from Ti-Ni shape memory alloys. The fabrication procedure was as follows: Ti-Ni ingots were made using a high-frequency induction vacuum furnace. The ingots were hot forged and hot extruded, which were followed by cold drawing and intermediate annealing to make wires with diameters of 1.0 mm. The final cold-work rate for wire rods was 34 %. These wire rods were processed to coil springs without further heat treatments except for the shape memory treatment. The mean diameter of the coil spring was 10 mm and number of active coils was 10.5. The alloys were composed of Ti-50.12at%Ni, Ti-50.39at%Ni, and Ti-50.63at%Ni and were annealed at 673 K, 723 K, and 753 K for 3.6 ks to memorize the shape at that time.

The transformation temperatures of the specimens were measured by the differential scanning calorimetry (DSC) and are shown in Table I.

2.2 Experimental procedure

The test temperatures are 293K, 303K, 313K, 323K, 333K, and 343K. The specimen was heated at an isothermal temperature and was elongated to a given maximum deflection of $\delta_{\max} = 65mm\ (\gamma_{\max} = 1.97\%)$, then the specimen was recovered by unloading. The loading and unloading rates were $\dot{\delta} = 0.153mm/s\quad(\dot{\gamma} = 4.64\times10^{-3}\%/s)$. The shear stress and strains were defined and calculated by the following equations,

shear stress: $\tau = \dfrac{8PD}{\pi d^3}$

shear strain: $\gamma = \dfrac{\delta d}{\pi n D^2}$

where

D : mean diameter of coil spring
d : wire diameter
n : number of active coils
P : load on spring
τ : shear stress
δ : deflection

γ : shear strain.

3. RESULTS AND DISCUSSIONS

3.1 Experimental results

Examples of experimental results are shown in Fig.1 and Fig.2 for specimens of Ti-50.39at%Ni annealed at 753K. From these figures it is revealed that coil specimens of this material tested at temperatures of 293K to 313K show the residual deformations at zero stress of the unloading state and that coil specimens tested at temperatures of 323K to 343K show no residual deformations. The specimens showing the residual deformations can recovered by heating at an temperature higher than the reverse transformation finish temperature A_f, and they behave as the shape memory alloys. The coil specimens tested at temperature of 323 to 343K behave as the superelastic material showing no residual deformations.

Figures 3 and 4 show the appearance of specimens before and after testing. Figure 4 shows the residual deformation after testing. The maximum deformation is about the double of that shown in Fig. 4. So it is understandable that the large deflection theory is necessary for analyzing the deformation of coil springs.

3.2 Deformation Analysis for Coil Spring Specimen

3.2.1 Analysis model

Deformation analyses of coil springs were performed by the finite element method (FEM) with the large deflection theory. A FEM program of ANSYS ver.10 was used. In the application of FEM the solid elements were used with 34,224 elements for the whole of a coil spring specimen. Figures 5 and 6 show the states of the mesh division.

Table I Transformation temperatures of Ti-Ni alloys

Material	T_{HT}/K	A_f/K	A_s/K	M_s/K	M_f/K	R_s/K	R_f/K
Ti-50.63at%Ni	673	312.9	287.0	250.8	200.3	320.4	303.8
	723	315.7	281.3	252.2	195.2	309.8	298.6
	753	311.0	285.6	250.9	210.6	302.1	293.2
Ti-50.39at%Ni	673	339.2	322.9	292.5	239.7	329.4	313.4
	723	336.6	320.0	284.4	250.1	318.5	309.1
	753	334.2	319.0	282.3	261.9	313.2	305.9
Ti-50.12at%Ni	673	357.5	334.3	312.2	266.1	332.5	322.6
	723	357.3	337.4	311.2	284.4	332.2	321.2
	753	359.8	341.3	316.3	295.3	330.5	319.8

T_{HT} : Heat treatment temperature

A_f : Reverse transformation finish temperature

A_s : Reverse transformation start temperature

M_s : Martensite start temperature

M_f : Martensite finish temperature

R_s : Rhombohedral start temperature

R_f : Rhombohedral finish temperature

3.2.2 Constitutive model

The constitutive model used for the FEM analyses was the one for the superelasic behavior of the shape memory

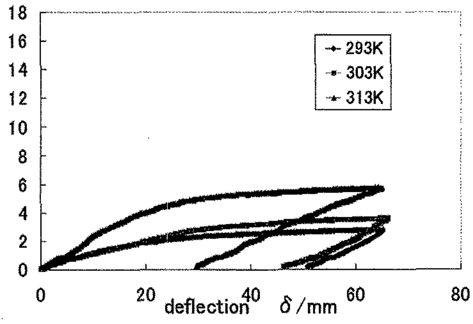

Fig.1 Load-deflection curves of coil spring specimens at T=293, 303, and 313K

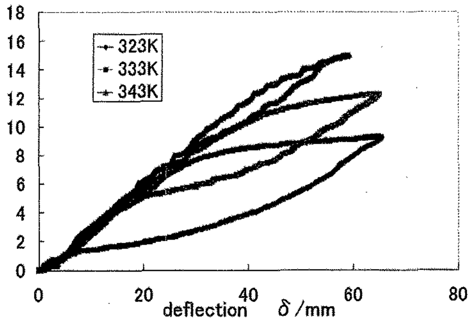

Fig.2 Load-deflection curves of coil spring specimens at T=323, 333, and 343K

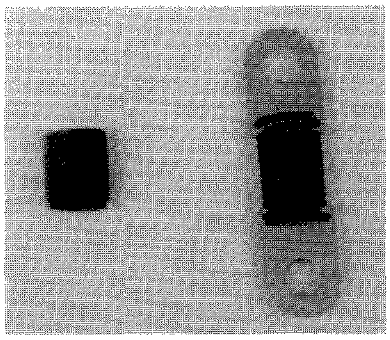

Fig.3 Appearance of test piece (before testing)

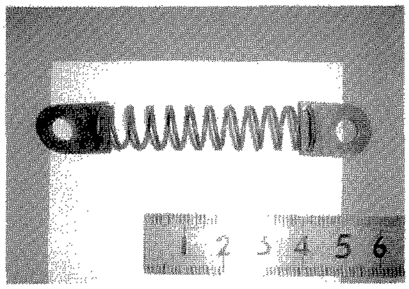

Fig.4 Appearance of test piece (after loading and unloading at 313K)

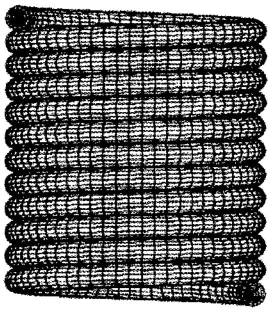

Fig.5 FEM meshes in a total spring

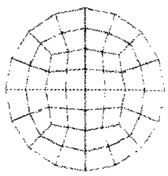

Fig.6 FEM meshes in the cross section of a spring

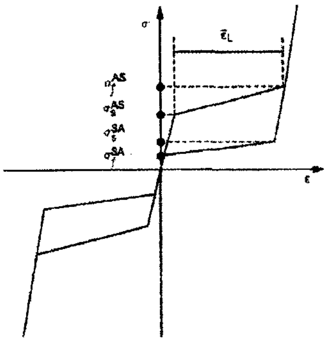

Fig.7 Material model as a built-in function of ANAYS for the superelastic behavior of shape memory alloys

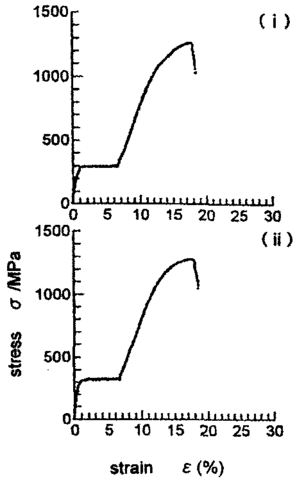

Fig.8 Stress-strain curves for wire specimens of Ti-Ni shape memory alloys under tensile loading at 333K

alloys which was given as a built-in function of the ANSYS program. In the constitutive model the uniaxial behavior of the material is modeled as shown in Fig.7. The material parameters used in the model were obtained from uniaxial tensile loading data of wire specimens. The sample values of material parameters were obtained from wire specimens of Ti-50.39at%Ni shape memory alloys annealed at 753K for the shape memory which were tested at 333K. Test results are shown in Fig. 8 and the obtained values of material parameters are given in Table II including estimated values for unloading states. For the multiaxial states the Mises equivalent stress theory was used.

Table II Values of material parameters for Ti-Ni alloys (Ti-50.39at%Ni) at 333K

E_A=65.5GPa	Young's modulus for Austenite
YMRT=14.1GPa	Young's modulus for Martensite
NU=0.3	Poisson's ratio
S_ASS=302MPa	starting stress value for the forward phase transformation
S_ASE=310MPa	final stress value for the forward phase transformation
S_SAS=155MPa	starting stress value for the reverse phase transformation (estimated)
S_SAF=116MPa	final stress value for the reverse phase transformation (estimated)
EPS_L=0.06	strain value for the phase transformation

3.3 Comparison between calculated results and experimental results

Figure 9 shows the comparison between calculated results and experimental results for the deformation of a Ti-50.39at%Ni shape memory alloy annealed at 753K for the shape memory and tested in the superelastic regime at 333K. It is revealed that the calculated results show a soft characteristic in the deformation behavior than experimental results.

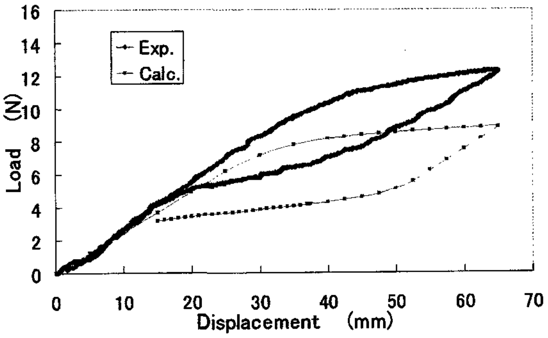

Fig.9 Comparison between calculated results and experimental results for a Ti-Ni shape memory alloys at 333K

3.4 Discussions

The discrepancy between calculated results and experimental results may be attributed to (1) the inadequacy of the equivalent stress approach to the superelastic deformation analysis of shape memory alloys in the multiaxial stress states and (2) the difference of work rate between coil spring specimens and wire

3.4.1 Discussions about the transformation stresses under multiaxial stress states

Hirakawa and Nishimura[4] conducted a molecular dynamics study for the transformation stresses of Ni-Al shape memory alloys under the multiaxial stress paths in the superelastic regime. They reported the transformation stresses become much greater in the shear stress path than in the tensile stress path. Though the material in our study is different from that in their study, the same effect may be expected. In the tensile tests of coil springs the major stress is the torsion (shear) stress, so the transformation stresses are expected to be grater than those shown in Fig.8 and Table II. Figure 10 shows the comparison between calculated results using the revised parameter values for the transformation stresses multiplied by 1.37 and experimental results. The agreement is very good. Therefore we may conclude the transformation stresses are greater in the shear stress state than those in the tensile stress state also in the Ti-Ni shape memory alloys.

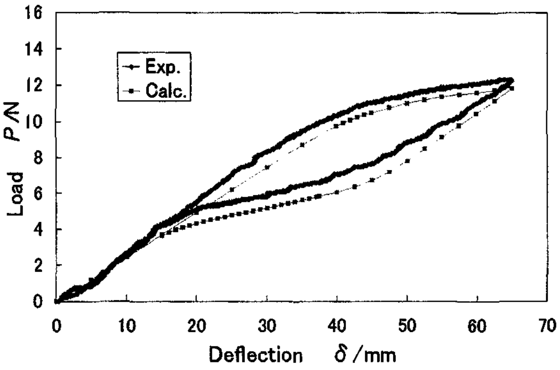

Fig.10 Comparison between calculated results using revised parameter values and experimental results

3.4.2 Discussions about the difference of the work rate

In the making procedure of specimens, wire rods specimens were processed to coil springs. So, the specimens of coil springs were suffered greater plastic work than wire specimens. This difference in work rate may influence the deformation behavior and can be the cause of discrepancy between the calculated results and experimental results shown in Fig.9. To investigate this aspect, we reprocessed both coil spring specimens and wire rod specimens fabricated in the manner described in the subsection 2.1 by the same solution heat treatment (1073K in Ar and water quenched) to erase the history of the prior cold work. Transformation temperatures were measured by DSC. They were $M_s = 281.8K$, $M_f = 275.9K$, $A_s = 281.1K$, and $A_f = 304.3K$. Figure 10 shows a sample of experimental results which were obtained by tensile loading and unloading of wire rod specimens of Ti-50.63at%Ni with the solution heat treatment. The test was conducted at 323K which is higher than the reverse transformation temperature A_f. It is revealed that these specimens showed the plastic deformation rather than the superelastic deformation even at a higher temperature than the reverse transformation temperature A_f. It is thought that this is because the dislocation structures in the material induced by cold working disappeared by the solution heat treatment and the slip deformation could easily occur even in the low stress condition. In this case there are no meanings for conducting further studies for the superelastic behavior of coil springs and wire rods. And it is concluded that in order to investigate the deformation behavior of coil springs and wire rods of the same work rate in the superelastic regime, the further process of aging after the solution heat treatment is needed to introduce the precipitations in the material for strengthening it.

4. CONCLUSIONS

The deformation behavior of coil springs of Ti-Ni shape memory alloys were experimentally investigated under various conditions. The analytical investigations were also conducted to compare the calculated results with experimental results. Some discrepancies were observed between the calculated results and the experimental results. It was concluded that in order to analyze the deformation behavior of coil springs more accurately, it was necessary to use the material parameters obtained from the experimental results of wire rod specimens composed of the same material of the same work rate as coil springs. And it was also pointed out that some efforts may be necessary to develop a more accurate constitutive model for multiaxial behavior of the shape memory alloys in the superelastic regime.

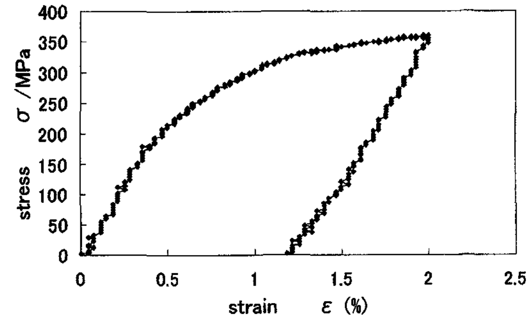

Fig.11 Stress-strain curve of wire rod specimen with the solution heat treatment tested at 323K

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