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Evaluation of Nucleation and Propagation Behavior of Phase Transformation on Shape Memory Alloy Plate

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Many problems have existed in usage of SMA such as change of properties (transformation temperature, Young's modulus) by process of fabrication, shape memory treatment, condition of phase and so on. Therefore, it has been pointing in recent years that expressing complicated phenomena using conventional constitutive relation of SMA have been difficult. It is necessary to construct novel constitutive relation that can describe these phenomena of SMA. In the present study, phenomena needed to construct novel constitutive relation of SMA, such as nucleation and propagation of phase transformation and so on, are measured using digital image correlation method. Then, the data measured from these experiments are evaluated to investigate the rule of nucleation and propagation of phase transformation.

Key words: Shape memory alloy, Shape memory effect, Pseudoelasticity, Macroscopic stress-strain relation, Inhomogeneous deformation behavior, Digital image correlation method.

1. INTRODUCTION

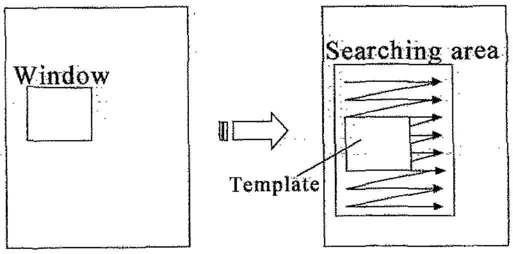
Shape memory alloy (SMA) has interesting characteristics such as shape memory effect, pseudoelasticity and recovery stress. Many basic investigations are conducted on the deformation behavior of SMA. However, many problems have existed in usage of SMA such as change of properties (transformation temperature, Young's modulus) by process of fabrication, shape memory treatment, condition of phase and so on. In addition, inhomogeneous deformation behavior of SMA is one of the above mentioned causes of problems. Some researchers investigated inhomogeneous deformation behavior of SMA [1-4]. For example, in-situ observation of propagation behavior using brittle coating [1] and evaluation of inhomogeneous deformation behavior using extensor meter for SMA [4]. Also, it is difficult for conventional internal state variable type constitute relation to express complicated deformation behavior of SMA. Therefore, it is necessary for using SMA on many fields to develop novel constitutive relation.

In this study, authors pay attention to the above mentioned inhomogeneous deformation behavior. The relations between macroscopic stress–strain curve and inhomogeneous deformation behavior are investigated. The digital image correlation method is used for measurement of the inhomogeneous deformation behavior. The displacement all over the surface of specimen can be calculated by comparing the distribution of gray level value between two images (undeformed image and deformed image) in digital image correlation method. The digital image correlation method is used in many fields because whole view field measurement is available without complicated optical system [5-6].

2. DIGITAL IMAGE CORRELATION METHOD

The image of a specimen taken before deformation is called undeformed image (reference image). The image taken after deformation is called deformed image. The displacement all over the image can be calculated by comparing undeformed image and deformed image. Most similar region of gray level value between two images is searched as shown in Fig.1. A window area is set up at undeformed image. The similar distribution of gray level value is searched at deformed image by following correlation function.

$$S\left(x,y,u_x,u_y,\frac{\partial u_x}{\partial x},\frac{\partial u_x}{\partial y},\frac{\partial u_y}{\partial x},\frac{\partial u_y}{\partial y}\right) = 1.0 - \frac{\sum\left[I_u(x,y)\times I_d(x^*,y^*)\right]}{\sqrt{\sum(I_u(x,y)^2)\times\sum(I_d(x^*,y^*)^2)}} \qquad (1)$$



(a) Undeformed image (b) Deformed image

Fig.1 Coarse searching of corresponding point

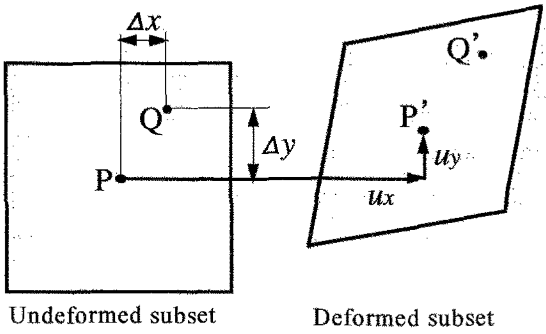
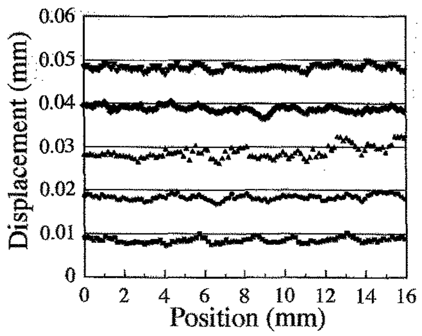
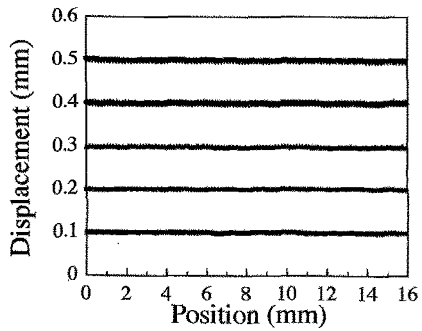


Fig.2 Subset before and after deformation



1) Small displacement



2) Large displacement

Fig.3 Relation between displacement and position under parallel movement

where, S is the correlation coefficient, I_u (x,y) is the gray level value at coordinate (x,y) of the undeformed image, $I_d(x^*,y^*)$ is the gray level value at coordinate (x^*,y^*) of the deformed image. Coordinate (x,y) and coordinate (x^*,y^*) are related by

$$\begin{aligned} x^* &= x + u_x + \frac{\partial u_x}{\partial x}\Delta x + \frac{\partial u_x}{\partial y}\Delta y \\ y^* &= y + u_y + \frac{\partial u_y}{\partial x}\Delta x + \frac{\partial u_y}{\partial y}\Delta y \end{aligned} \tag{2}$$

where, u_x and u_y are the displacement of x direction and y direction in the center of a calculation area. x and y are the distance from the center of a calculation area to a coordinate (x,y). Figure2 shows the relation between the calculation area before and after deformation after coarse searching. If the points P and Q move to points P' and Q', an amount of movement of point P is displacement u_x, u_y. Also, coordinate of point Q' is expressed by Eq.(2). The displacement can be determined by searching for six parameters, u_x, u_y, $\partial u_x/\partial x$, $\partial u_x/\partial y$, $\partial u_y/\partial x$, $\partial u_y/\partial y$, which make S in Eq.(1) minimize. The gray level value is complemented by the method using the bilinear function and the spline function to detect displacement in the resolution of 1 pixel or less. Also, in order to reduce the time of calculation, the Newton-Raphson method is used for the calculation of correlation. That is, the calculation is performed repeatedly so that all values acquired by partial differentiating the Eq. (1) with respect to six unknown variable are 0. If the above methods are combined, it is possible to determine the displacement in the accuracy of about 0.02 pixels.

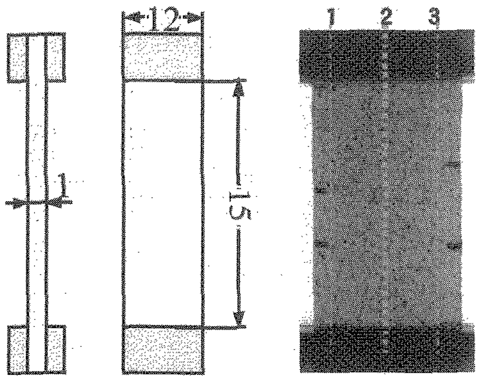


Fig.4 Specimen configuration

3. MEASUREMENT OF DISPLACEMENT USING DIGITAL IMAGE CORRELATION METHOD

The validity of the distribution of displacement obtained from the digital image correlation method was examined. The specimen was moved in parallel with the tensile machine, and the displacement obtained from the digital image correlation method was compared with the displacement obtained from the crosshead of tensile machine. The random pattern was created by the spray of black and white on the surface of specimen. The specimen was moved from 0mm to 0.05mm as the small displacement and the image was taken every 0.01mm. Also, the specimen was moved from 0mm to 0.5mm as the large displacement and the image was taken every 0.1mm. The undeformed image was the image before moving and the deformed image was the image after moving. Then, the correlation was performed using these images. Where, 1pixel was 0.03mm in present experiments.

Figure3 shows the results obtained from these experiments. The horizontal axis shows the position in the longitudinal direction (direction of movement) of the specimen, and the vertical axis shows the displacement in each position along the longitudinal direction. Fig.3 shows that the displacement obtained from the digital image correlation method are mostly agree with the displacement from the crosshead of tensile machine although the displacement in 0.01mm order shows a little dispersion.

4. INHOMOGENEOUS DEFORMATION BEHAVIOR ARISING IN SMA

SMA shows the inhomogeneous deformation behavior. This inhomogeneous deformation behavior becomes an issue when SMA is used as a structure in applications. Past investigations for deformation behavior of SMA have been discussed only from the macroscopic stress-strain curves obtained from tensile tests. Therefore, investigating the relation between the inhomogeneous deformation behavior and the macroscopic stress-strain curve is very important for considering the application of SMA.

4.1 Specimen and experimental procedure

NiTi SMA plate (50.5Ni49.5Ti [at.%]) was used for specimen as shown in Fig.4. The shape memory treatment was done for specimen at 400℃ and 30min. The thermo-mechanical training (tensile loadng, unloading, heating) was given to specimen in order to secure stabilized deformation behavior of SMA. The random pattern was created by the spray of black and white on the surface of specimen.

The tensile loading and unloading were performed for NiTi alloy plate in two temperature regions which the SMA showed the shape memory effect (26℃) and pseudoelasticity (60℃). Then, the relation between the macroscopic stress-strain curves and the inhomogeneous deformation behavior arising in SMA was investigated using the digital image correlation method. The tensile loading and unloading tests were performed at strain rate 0.5%/min. The images of specimen under deformation were taken every 20 second.

4.2 Macroscopic stress–strain curve and inhomogeneous deformation behavior (nucleation and propagation behavior of phase transformation) of SMA

Figures5 and 6 show the stress-strain curves obtained from the tensile loading and unloading tests in

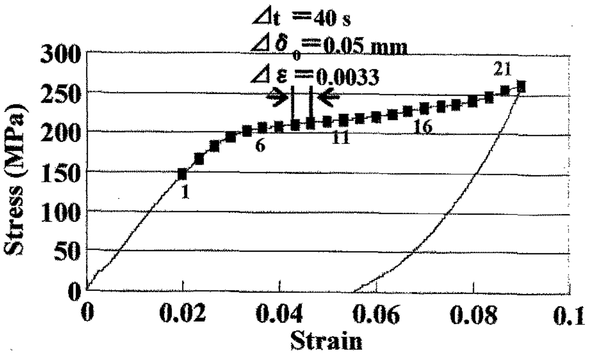


Fig.5 Stress-strain relation for SMA plate in the temperature region of the shape memory effect

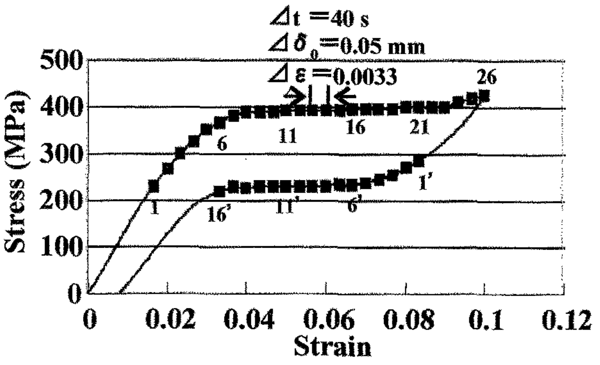


Fig6. Stress-strain relation for SMA plate in the temperature region of the pseudoelasticity

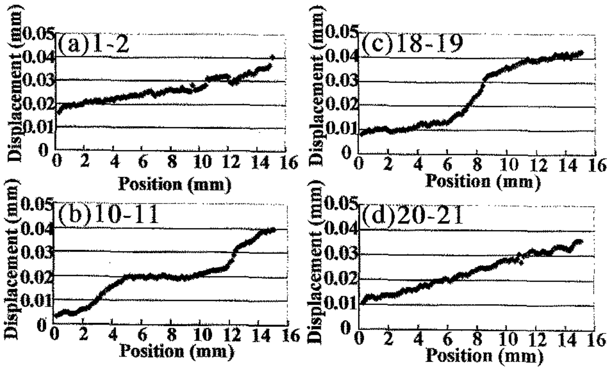


Fig.7 Displacement on line2 in the temperature region of shape memory effect

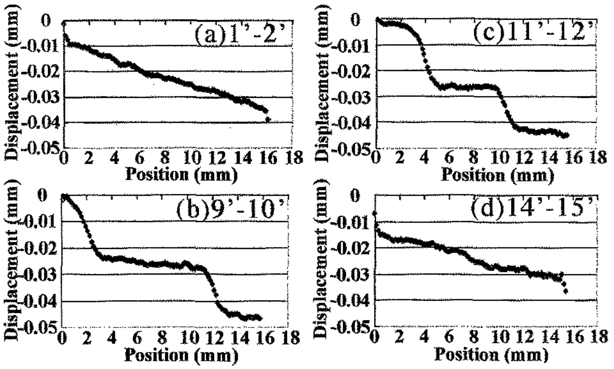


Fig.8 Displacement on line2 in the temperature region of pseudoelasticity

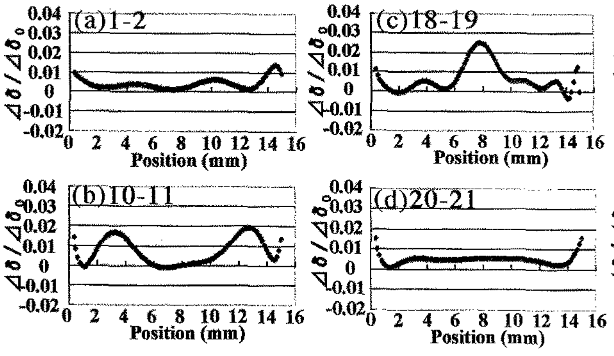


Fig.9 Deformation ratio on line2 in the temperature region of shape memory effect

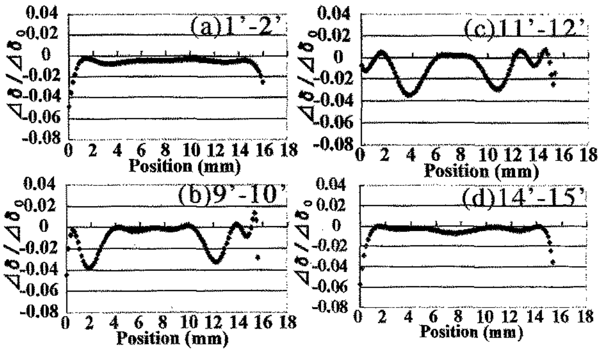


Fig.10 Deformation ratio on line2 in the temperature region of psuedoelsticity

the temperature region showing shape memory effect and pseudoelasticity, respectively. In this experiment, the propagation behavior during stress induced martensitic transformation and reverse transformation was measured. Correlation was performed in each section of 1-21 in the Fig.5 and 1-26, 1'-16' in Fig.6. Strain increment for each section is $\Delta\varepsilon$=0.0033 in Figs.5 and 6. Then, the displacement - position along the longitudinal direction of the specimen on the broken line (Line2) in Fig.4 relation is shown in Figs.7 and 8, and the deformation ratio–position relation is shown in Figs.9 and 10 for temperature region of shape memory effect and pseudoelasticity. Deformation ratio is value that the increment ($\Delta\delta$) of the displacement every 0.15mm along the longitudinal direction of the specimen is divided by the increment ($\Delta\delta_0$) of the whole displacement of specimen. Also, experimental data of displacement-position relation was smoothed by the least squares method.

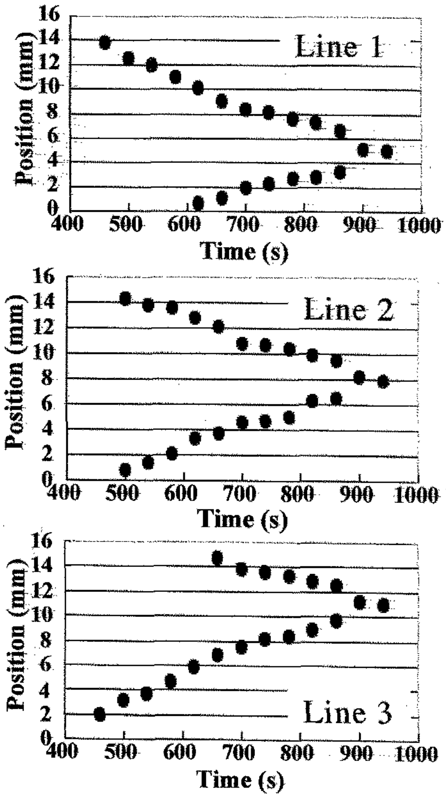


Fig.11 Position of peak deformation ratio as a function of time on lines1,2,3 in the temperature region of shape memory effect

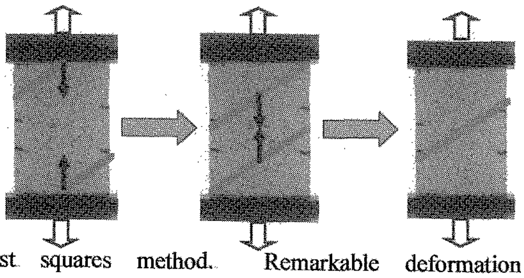


Fig.12 Schematic illustrations of the propagating of phase transformation under tensile loading

behavior for correlated sections are shown in figures.

As shown in Fig.9, it is found from deformation ratio –position relation that NiTi plate shows uniform deformation up to start of transformation in stress–strain curve. Then, it is found from deformation ratio–position relation that SMA plate shows propagation of phase transformation during stress induced martensitic transformation. The transformation propagates from the both ends to the center of the specimen. And, NiTi plate shows uniform deformation after stress induced martensitic transformation. Also, the result of propagation behavior of phase transformation (stress induced martensitic transformation) in the temperature region showing pseudoelasticity showed the same behavior in shape memory effect. Then, the propagation behavior of phase transformation for reverse transformation was seen during unloading process showing pseudoelasticity as shown in Fig.10. The reverse transformation propagate from the both ends to the center of the specimen.

Figure11 shows relation between peak position of deformation ratio and time during transformation. Speed of propagation can be obtained from the slope of this relation. Furthermore, the inhomogeneous deformation behavior was investigated not only on the center line (Line2) of the specimen but also on the right line (Line1) and the left line (Line3) shown in Fig.4. Distribution of propagation behavior can be investigated from these figures. The transformation had a fixed angle along the longitudinal direction of the specimen, propagating from the both ends to the center of the specimen.

5. CONCLUSION

The relation between the macroscopic stress-strain curve and the local inhomogeneous deformation behavior of NiTi SMA was investigated by using the digital image correlation method. The obtained results were as follows. The propagation of the phase transformation during the stress-induced martensitic transformation and austenite transformation propagate from the both ends to the center of the specimen. Furthermore, the propagation behavior was investigated from position of peak deformation ratio-time relation. The transformation had a fixed angle along the longitudinal direction of the specimen, propagating from the both ends to the center of the specimen.

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