On the Full-Field Deformation of Single Crystal CuAlNi Shape Memory Alloys—Stress-Induced $\beta_1 \rightarrow \gamma'_1$ Martensitic Transformation

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Abstract: Using high sensitivity Moiré interference technology, the full deformation fields about the stress-induced martensitic transformation $\beta_1 \rightarrow \gamma'_1$ of single crystal CuAlNi shape memory alloys (SMAs) are obtained. A straight and sharp interface between martensite and parent phases and its motion during transformation process are clearly observed. The elastic anisotropic properties of the crystal are also quantitatively characterized by this technique. The results show that there is no deformation incompatibility between the two phases, which is different from that of pseudoelasticity where another stress-induced martensitic transformation $\beta_1 \rightarrow \beta'_1$ occurs. The present results provide an accurate experimental solution for the phase transformation problem in solids.

1. INTRODUCTION

The constitutive behaviors of single crystal shape memory alloys (SMAs) under externally applied stress are strongly dependent on temperature and crystal orientation. According to the testing temperature, the single crystal CuAlNi SMAs present very different phenomena under a certain stress[1~4]. If the testing temperature is below M_s , the material is in the martensite state initially and the different martensitic variants will be reoriented to the most favorite one under the stress. If the testing temperature is above M_s , the material initially is parent phase and will be transformed to martensite under a certain stress. Generally this stress-induced martensite can be further divided into two classes. When the temperature is between M_s and A_f , the lattice structure change associated with the transformation is from DO_3 (β_1) to $2H$ (γ'_1) and part or all of the stress-induced martensite will remain after unloading. When the temperature is above A_f , the martensite has a structure of $18R$ (β'_1), which will disappear on the removal of stress because the martensite is unstable at this temperature. In establishing constitutive model of single SMAs, it is very important to know the effects of microstructure on the macroscopic deformation behavior, and to have a quantitative picture of the macro-micro relationship and microstructure evolution. To achieve this aim, a full-field deformation measurement is required.

Moiré interferometry has been used widely in the experimental mechanics to perform various kinds of in-plane displacement measurement[5]. It has several excellent properties like real-time, high sensitivity to in-plane displacement, high spatial resolution and high quality fringe patterns. These unique features make it an exceptionally attractive tool for measuring the microstructure sensitive deformation field of SMAs [6,7]. In the present paper, we investigate the $\beta_1 \rightarrow \gamma'_1$ martensitic transformation of CuAlNi single crystal SMAs under uniaxial tension by using high sensitivity Moiré interferometry. Some important deformation features of the material at different stages of transformation were first quantitatively revealed.

2. EXPERIMENTAL PROCEDURE

The tensile specimen was cut from the CuAlNi (Cu-13.7%Al-4.18%Ni (wt%)) shape memory alloy single crystal ingot (27mm diameter with 60mm long). This single crystal rod was produced by Prof. Tan

Shusong (Central South University of Technology, China) using the improved Bridgeman method. The specimen was cut from the ingot using a wire-cutting electrical discharge machine (EDM). The shape and size of the specimen is shown in Fig.1, and the thickness of the specimen is 2mm. The specimen was heat treated at 850°C for 30 minutes and then quenched into 120 °C oil. The transition temperature of the specimen was measured by Differential Scanning Calorimeter (DSC) ($M_s = 3^\circ\text{C}$, $M_f = 6^\circ\text{C}$, $A_s = 35^\circ\text{C}$, $A_f = 45^\circ\text{C}$) to make sure that the initial state of the specimen is austenite (β_1 phase) and the stress-induced martensite will be retained after unloading. Before Moiré experiments, a tensile test was carried out on a MTS machine at room temperature (about 22°C) with a cross-head speed of 5×10^{-3} mm/sec. The tensile strain was measured by an extensometer with gauge length of 25mm and the load was measured by a 5KN load cell. The specimen for Moiré test was hand-polished using 600 grit silicon carbide paper, and then a high frequency crossed-line grating of 1200 lines/mm was replicated on the specimen by epoxy cement. The orientation of the tensile loading axis with respect to the lattice axes of the parent phase is (0.087, -0.796, -0.605).

Fig.1. The shape of the specimen (all dimensions in mm)

Fig.2 The stress-strain curve under uniaxial tension

The basic principle of Moiré interferometry is described in detail in the book of Post, D., Han, B. and Ifju, P.[5]. In this method, the grating deforms together with the underlying specimen. Uniaxial loading is performed by a specially designed tensile loading frame with a load cell. During the loading, both the elastic deformation due to the stress and the deformation due to the transformation will contribute to the whole displacement fields. The resulting fringe patterns represent contours of constant in-plane displacements u and v , which are displacement components in x (transverse) and y (axial) directions, respectively (Fig.1).

3. RESULTS AND DISCUSSION

Figure 2 shows the stress-strain curve of this material. It is linear at the beginning and then shows very large serration associated with the formation of stress-induced martensite. At the end of the curve, the stress increases rapidly and we observed that the full gauge length is occupied by the martensite, this means that $\beta_1 \rightarrow \gamma_1$ martensitic transformation has finished. The martensite is stable at room temperature and most of them remains on remove of the stress.

Figure 3 (a) and (b) respectively shows the fringe patterns of the u and v elastic displacement fields before the transformation happens. It is seen that the strain (and so the stress) is quite uniform except the regions near the two ends of the specimen. And it is also seen that there exists shear strain under uniaxial tension, this is due to the fact that the cubic parent phase is elastically anisotropic and the principle axes of the stress tensor are not coincident with the lattice axes of the material.

Fig.3 The elastic u (a) and v (b) displacement fringe patterns before transformation

Fig.4 The u (a) and v (b) displacement fringe patterns corresponding to point A in the curve of Fig.2

(a)

(b)

Fig.5 The enlarged u (a) and v (b) displacement fringe patterns of the square I in Fig.4

(a)

(b)

Fig.6 The enlarged u (a) and v (b) displacement fringe patterns of the square II in Fig.4

With the increase of the applied stress, transformation occurs by a sudden formation and propagation of martensite accompanying a rapid load drop (Fig.2). Fig.4 (a) and (b) are respectively the u and v displacement fields corresponding to point A ($\sigma_{yy} = 78.5\text{MPa}$) of the stress-strain curve. It can be seen clearly that the habit plane is inclined in an angle of 55.5° with the loading axis and there still exist some parent phase within the martensite domain. Fig.5 (a), (b) and Fig.6 (a), (b) are the amplified fringe patterns of the square areas in Fig.4, respectively. The total strain ε_{ij} in the parent phase is the elastic strain, *i.e.*, $\varepsilon_{ij} = \varepsilon_{ij}^e$ and the values are: $\varepsilon_{xx}^e = -0.08\%$, $\varepsilon_{yy}^e = 0.18\%$ and $\varepsilon_{xy}^e = 0.08\%$. The transformation strain ε_{ij}^t ($\varepsilon_{ij}^t = \varepsilon_{ij} - \varepsilon_{ij}^e$) inside the martensite are: $\varepsilon_{xx}^t = -3.41\%$, $\varepsilon_{yy}^t = 3.60\%$ and $\varepsilon_{xy}^t = 0.79\%$. Comparing the above results with the strain in Fig.2, we find that the transformation strain measured by Moiré ($\varepsilon_{yy}^t = 3.60\%$) is in good agreement with the maximum residual strain (3.70% at point B) in the stress-strain curve. We can also see that the interface is straight and there is no deformation incompatibility between martensite and parent phases (Fig.5, 6). This implies that the martensite formed has an internally twinned structure. This is different from the case of pseudoelasticity[7] where both habit plane variant formation and detwinning are possible. Detailed microstructure identification by using Electron Back Scattering Diffraction (EBSD) is under way.

4. CONCLUSIONS

By using high sensitivity Moiré interferometry, a full-field deformation patterns of the stress-induced $\beta_1 \rightarrow \gamma_1$ martensitic transformation in single crystal CuAlNi SMAs are first obtained. A straight and sharp interface between martensite and parent phases and its motion during transformation process are clearly observed. All the microstructure related properties such as the strain jump over the interface, the habit plane orientation and the strain distribution in both phases *etc.*, are all quantitatively characterized by this technology. The results show that there is no deformation incompatibility between the two phases, which is different from that of the pseudoelasticity where the phase transformation of $\beta_1 \rightarrow \beta_1'$ occurs. The present results provide an accurate experimental solution for the phase transformation problem in solids.

Acknowledgments

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