Creep Deformation of Single Al-Ni-Co Decagonal Quasicrystals

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The compressive creep deformations at elevated temperatures have been investigated using single decagonal Al-Ni-Co samples prepared by Czochralski method. The creep deformation is characterized by a significant anisotropy of activation energy between the different compressive directions of 2-fold symmetry axis (330 kJ/mol) and 10-fold symmetry axis (120 kJ/mol). The difference of deformation mechanisms along the 2-fold and 10-fold axes has been examined by the HRTEM observation which showed varied cluster rearrangements.

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I. Introduction

It has earlier been recognized that quasicrystalline alloys are extremely brittle⁽¹⁾, which was considered as a direct consequence of the absence of periodicity. At room temperature, dislocations in quasicrystals are exerted by an enormous dragging stress due to formation of a stacking fault, a phason strain field and a chemical disorder. Although quasicrystals are inherently brittle at room temperature, significant plasticity at elevated temperatures has been observed in quasicrystalline alloys. For plastic deformation mechanism in quasicrystals, there are two different interpretations: one⁽²⁾⁻⁽⁴⁾ is that the dislocations motion plays a significant role in the plastic deformation, and the other⁽⁵⁾ is that the atomic diffusion brings about the plastic deformation. Actually, although dislocations can be well defined⁽⁶⁾ in decagonal quasicrystals, their Burgers vectors have always a non-zero component in the perpendicular space. This implies that any motion of dislocation must be accompanied by phason redistributions over large distance. So, the smooth glide of dislocation in a quasiperiodic lattice occurs only at sufficiently high temperatures with enormous diffuser efficiency to recover the phason strain field around the region swept by the dislocation. In order to reveal the feature of plastic deformation mechanism in a quasiperiodic lattice, mechanical testing for single decagonal quasicrystals with several loading directions along quasiperiodic and periodic directions is an important study. The plastic deformations of decagonal quasicrystal at high temperatures of Al-Ni-Co⁽⁷⁾ and Al-Cu-Co⁽⁸⁾ single ingots have been reported. The notable resemble points between these reports are summarized as follows, 1) compression deformability along 45° from the 10-fold axis is the most superior than other directions, 2) the stress dependence of the activation volume shows a hyperbolic relation which does not de-

pend on compression directions.

In this paper, compressive creep deformations along periodic and quasiperiodic directions in Al-Ni-Co single decagonal samples at elevated temperatures were investigated by a modified hot-press machine with loading by a deadweight. We tried to reveal the difference of plastic deformation mechanism between periodic and quasiperiodic directions by HRTEM observations, which can be revealed microscopic structural differences between the samples compressed along quasiperiodic and periodic directions.

II. Experimental Methods

The samples used in the present study were cut out from an $Al_{72}Ni_{12}Co_{16}$ single decagonal sample⁽⁹⁾ with a shape of rectangular parallelepiped. Beforehand, the samples were fully annealed at 1150 K for 100 h to remove micro-segregation and conventional strain. Creep testing was performed by a hot press machine which was improved in loading mechanism with deadweight and in automatic displacement measurement system. Morphologies of the creep deformed samples were observed by optical microscopy (OM) and scanning electron microscopy (SEM). Microscopic structural changes in atomic scale of deformed samples along quasiperiodic and periodic directions were analyzed by high resolution transmission electron microscopy (HRTEM).

III. Results and Discussion

Figure 1(a) shows outer appearance of an $Al_{72}Ni_{12}Co_{16}$ single decagonal sample prepared by the Czochralski method, and (b) shows the back scattering X-ray Laue diffraction pattern taken from the growth direction of 10-fold symmetrical axis. The growth rate of the Czochralski method was as low as 0.5 mm/h so as to suppress the defects due to the micro segregation. The

Fig. 1 (a) Outer appearance of an $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ single quasicrystal with distinct facet-planes of 10-fold symmetry. (b) X-ray Laue diffraction pattern of the 10-fold symmetry taken from the growth direction.

as-grown single samples were cut out into the several samples, and then fully annealed at 1150 K for 100 h to remove micro-segregation and conventional strain. After above mentioned processes, the samples were used for compressive creep testing at several elevated temperatures.

Compression creep experiments provide a method to evaluate the deformation characteristics of materials. For ordinary crystalline materials, the steady-state creep rate can be described⁽¹⁰⁾ by a power-law relationship,

$$d\varepsilon/dt = B\sigma^n \exp(-Q/RT) \quad (1)$$

where B is a material constant, σ is the applied stress, Q is the activation energy, T is the absolute temperature, R is the gas constant, and n is the stress exponent. To determine the activation energy Q in eq. (1), the strain rate $d\varepsilon/dt$ was measured by holding σ constant as 98 MPa at varied temperatures as 1086, 1107 and 1143 K. Creep deformation data with compressive directions along quasiperiodic and periodic directions in single Al-Ni-Co decagonal samples are shown in Figs. 2 and 3, respectively. Figure 2 shows the strain as a function of time for the single decagonal sample with compressive direction along a quasiperiodic direction at 1086, 1107 and 1143 K. Figure 3 also shows the strain as a function of time for the single decagonal sample with compressive direction along the periodic direction at 1086, 1107 and 1143 K. These curves show that the steady-state creep deformation exhibits after 5 ks loading. For both 10-fold and 2-fold compressive directions, $\ln(d\varepsilon/dt)$ is plotted against T^{-1} in Fig. 4. The notable point in this figure is that the pre-exponential factor in eq. (1) is quite different between the two samples. As a result, the strain rate becomes reversed with temperature change. The value of the activation energy was determined to be approximately 330 kJ/mol for the samples with compressive direction along quasiperiodic direction and to be approximately 120 kJ/mol for the samples with compressive direction along periodic direction.

After deformed at 1107 K, surface morphologies of samples were observed to determine the existence of slip bands or micro cracks. Figure 5(a) shows schematic il-

Fig. 2 Creep deformation strain as a function of time for the single domain sample with compressive direction along a quasiperiodic direction at 1086 1107 and 1143 K.

Fig. 3 Creep deformation strain as a function of time for the single domain sample with compressive direction along a periodic direction at 1086, 1107 and 1143 K.

lustration of the sample with the compressive direction along the periodic direction (10-fold direction), and after deformed, surface morphologies at the observation point

Fig. 4 Relation between the $(d\epsilon/dt)$ and $1/T$ of the two samples.

Fig. 5 (a) Schematic illustration of specimen with compressive direction along the periodic direction (10-fold direction). (b) Optical micrograph of the deformed surface morphologies at the observation point in (a). (c) SEM image of the deformed surface morphology.

in (a) were observed by OM (b) and by SEM (c). In the figure (b), there is no slip mark which can be recognized by mismatching of scratch marks by OM observation. So, we tried to observe carefully on the deformed surface morphology by SEM, and we could observe a lot of slight wiggles of scratch marks, which implies the existence of homogeneous flow deformation region. **Figure 6(a)** shows schematic illustration of specimen with the compressive direction along a quasiperiodic direction (2-fold direction), and deformed surface morphologies at the observation points in (a) were observed by SEM. Figure 6(b) shows that the wide slip band lies along 2-fold direction perpendicular to the compressive direction. And mismatchings of scratch marks were observed between up-side and down-side of the slip band. The slip band is guessed not to be formed by any dislocation glides but by cracking and/or inhomogeneous flow deformation due to atomic diffusion, because the slip band is accompanied by a lot of distinct protruded nodules on the surface. In the side view of the nodule shown in Fig. 6(c), the morphology of the nodule at the end of slip band shows approximately the half shape of decagonal prism which corresponds to the 10-fold symmetry of the matrix decagonal phase. In creep deformation morphologies of ordinary crystalline materials, the nodule growth is seen around cracks with high speed diffusion on fresh surface by the cracking. The existence of cracking marks on creep deformation morphologies imply that the homogeneous compressive deformation along quasiperiodic direction of the decagonal structure is almost impossible even at the slow strain rate of $4 \times 10^{-6} \text{ s}^{-1}$ at 1107 K.

Fig. 6 (a) Schematic illustration of specimen with compressive direction along a quasiperiodic direction (2-fold direction). (b), (c) SEM images of the deformed surface morphologies at observation points in (a).

In order to discuss about the anisotropy of activation energy for creep deformation, only the macroscopic deformation morphologies are not sufficient to conclude the difference of deformation mechanism between quasiperiodic and periodic compressive directions. Assuming that the anisotropy of deformation mechanism is caused by structural anisotropy of the decagonal structure, microscopic observation in atomic scale by HRTEM will reveal the structural change between the

states before and after deformation. **Figure 7(a)** shows the lattice image of an Al-Ni-Co single sample after anneal treatment under no loading at 1107 K in order to supply the same thermal effect of other creep deformed samples, and (b) shows schematic illustration of pentagonal tiling pattern of decagonal atom clusters which are seen as the ring contrast with 2 nm in diameter on the HRTEM image (a). The pentagonal tiling with 5 decagonal clusters exists everywhere homogeneously on Fig. 7(b), which means the superior quasicrystallinity of the Al-Ni-Co after the annealing. **Figure 8(a)** shows the lattice image of an Al-Ni-Co single sample after compressive creep deformation along periodic direction at 1107 K, and (b) shows schematic illustration of pentagonal tiling pattern of decagonal clusters. This figure points out the drastic structural change after creep deformation along periodic direction where crystalline domains with periodic rearrangement of decagonal clusters like an approximant phase exist. The periodic tiling region seems to occur preferentially at deformed area by the compressive force perpendicular to this figure, and the periodic tiling is also characterized by a linkage of atom clusters with a distance about 2 nm to keep the perfect decagonal cluster shape through the deformation. The decagonal structural model⁽¹¹⁾ shows that a decagonal cluster with diameter of 2 nm is constructed by the centered decagonal cluster with diameter 1.38 nm and surrounded ten pentagonal clusters with side length about 0.47 nm. The linkage of the atom clusters with a distance of about $2/\tau$ nm (τ : golden ratio) causes a chemical disorder⁽¹²⁾ in the structure of centered decagonal cluster in decagonal cluster structure model. However, the atom clusters in the distance about 2 nm can move their positions of centered decagonal clusters ($d = 1.38$ nm) without chemical mismatching by flow of surrounding pentagonal clusters, which can be considered as cutting atomic pairs of Al-Al mainly. Assuming that this deformation mechanism play a role of relaxation of applied stress at deformation area, the value of activation energy for creep deformation about 120 kJ/mol can be understood. The activation energy means that the preferential Al diffusion brings about the creep deformation of 10-fold compressive direction, since the value is close to the self diffusion activation energy for Al about 122 kJ/mol⁽¹³⁾. As a result, the deformation along the periodic direction causes a lot of the periodic linkage of the atom clusters with the distance of 2 nm.

Figure 9 shows the lattice image of an Al-Ni-Co single sample after compressive creep deformation testing along a quasiperiodic direction at 1107 K, and (b) shows schematic illustration of pentagonal tiling pattern of the decagonal clusters. In this figure, (a) and (b) are similar to those of Fig. 7, which was prepared without loading. And the high activation energy for creep deformation about 330 kJ/mol indicates the difficulty of creep deformation along the quasiperiodic direction; the activation energy is almost equal to the interdiffusion energy in ordered Al-TM intermetallic compound about 313

Fig. 7 (a) Lattice image of an Al-Ni-Co single sample after anneal treatment at 1107 K without loading. The incident beam is parallel to the 10-fold direction. (b) Schematic illustration of pentagonal tiling pattern (modified Penrose tiling) of decagonal atom clusters.

Fig. 8 (a) Lattice image of an Al-Ni-Co single sample after creep deformed along periodic (10-fold) compressive direction at 1107 K. The incident beam is parallel to the 10-fold direction. (b) Schematic illustration of pentagonal tiling pattern (modified Penrose tiling) of decagonal atom clusters.

Fig. 9 (a) Lattice image of an Al-Ni-Co single sample after creep deformed along quasiperiodic (2fold) compressive direction at 1107 K. The incident beam is parallel to the 10-fold direction. (b) Schematic illustration of pentagonal tiling pattern (modified Penrose tiling) of decagonal atom clusters.

$\text{kJ/mol}^{(14)}$, and the value is also almost equal to the activation energy of creep deformation of poly-grained decagonal sample⁽¹⁴⁾. The deformation along the quasiperiodic direction demonstrates that no distinct structural change occurs, because the deformation acts in both of the linkages of the atom clusters with the distance of 2 nm and $2/\tau$ nm. The high activation energy also points out that the deformation along the quasiperiodic direction occurs by cutting Al-TM pairs mainly. The deformation mechanism causes a chemical disorder⁽¹⁰⁾ in centered decagonal clusters (1.38 nm) and increases the mismatching of the tiling. **Figure 10** shows quasiperiodicities of different three samples obtained by projecting a two-dimensional periodic lattice, (a) and (b) show those of after creep compressive deformation at 1107 K along periodic and quasiperiodic directions, respectively, and (c) shows that after annealed at 1107 K without loading. In the figure (a), average slope of the strip is neither τ nor $1/1$, and the strip is somewhat wandering and in some regions it is close to $1/1$. This situation is introduced mainly by the fluctuation of linear phason strain. In the figure (b), average slope of the strip is close to τ , and the slope is also wandering upward or downward from the line with $\tan \theta = \tau$. This situation is realized mainly by the introduction of random phason strain, because the degree of wandering of $G_{\perp}$ component after annealing at 1107 K without loading shows smaller than that for the periodic-directionally compressed sample (c.f. Fig. 10(b) and (c)). Consequently,

from the analysis of the quasiperiodicity by projecting a two-dimensional periodic lattice, the difference between the deformation mechanisms is characterized by the different type of introduced phason strain. These facts support the structural difference between Figs. 8 and 9, because the generation of one-sided linkage of atom clusters with a distance 2 nm causes the rhombic crystalline approximant regions in the sample. The linear phason mode of $\tan \theta = 1/1$ is equivalent to the tile rearrangement from the Penrose quasiperiodic tiling to the rhombic periodic tiling. The anisotropy of creep deformation between quasiperiodic and periodic compressive directions implies the deformation along periodic direction is easier than that along quasiperiodic one. From the morphological observation after deformation, no distinct deformation marks were seen on the samples with compressive direction along a quasiperiodic direction. The deformation in quasiperiodic atomic plane (10-fold symmetrical atomic plane) will hardly occur, because the 10-fold atomic plane shows tightly grown-up chemical order in every direction. Besides, the creep deformation along the periodic direction exhibits a low activation energy, an atom cluster rearrangement to periodic one and the existence of linear phason strain. This is, an easy creep deformation mechanism appears in the periodic direction with a partial structural transformation to rhombic crystalline regions.

Fig. 10 (a) Quasiperiodicity of the sample after creep deformed at 1107 K along periodic direction by projecting a two-dimensional periodic lattice. (b) Quasiperiodicity of the sample after creep deformed at 1107 K along quasiperiodic direction by projecting a two-dimensional periodic lattice. (c) Quasiperiodicity of the sample after anneal treatment at 1107 K without loading by projecting a two-dimensional periodic lattice.

IV. Summary

The compressive creep deformation at elevated temperatures has been investigated using single Al-Ni-Co decagonal quasicrystal prepared by the Czochralski method. The activation energy and deformation morphology changes were examined in the samples with the

compressive direction along quasiperiodic and periodic directions. The different deformation mechanisms between 2-fold and 10-fold axes have been suggested by the HRTEM images with varied cluster rearrangements. The results obtained are summarized as follows:

(1) The creep deformation of single Al-Ni-Co samples was characterized by a significant anisotropy of activation energy between the different compressive directions: 2-fold symmetry axis (330 kJ/mol) and 10-fold symmetry axis (120 kJ/mol).

(2) HRTEM image of the deformed sample with compressive direction along the periodic direction shows a large amount of atom cluster rearrangement regions with a crystalline rhombic tiling.

(3) The random phason strain was introduced by the compressive deformation along a quasiperiodic direction. On the other hand, the linear phason strain was introduced by the compressive deformation along the periodic direction.

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