Plastic Deformation of Mg-Zn-Y Icosahedral Quasicrystals under Confining Pressure

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Deformation experiments of Mg-Zn-Y icosahedral quasicrystals under a hydrostatic confining pressure have been performed to investigate their deformation mechanism in a low temperature range. The temperature dependence of the yield stress has been successfully measured, for the first time, down to room temperature. An irregular behavior has been found in the temperature dependence: the yield stress increases rapidly with lowering temperature down to 373 K and it becomes almost constant in the temperature region lower than 373 K. The origin of such an irregular temperature dependence is discussed in terms of possible transition between two different dislocation processes: glide and climb.

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1. Introduction

In general, quasicrystals are brittle at room temperature and can only be plastically deformed at high temperatures above about 0.75Tm (Tm: melting temperature). In the high temperature range, systematic deformation experiments have so far been performed for the quasicrystals of various alloy systems (see reviews1–3)). Those experiments have shown some common features in the plastic behavior of the quasicrystals such as marked work-softening after the yielding, large temperature and strain-rate dependences of the yield stress, etc. In addition, transmission electron microscopy (TEM) observations have confirmed that the high-temperature plastic deformation of the quasicrystals is due to dislocation motion.4–6) Here, a majority of the TEM observations have indicated that the deformation is controlled by glide of dislocation. However, in some experiments dislocation climb has been shown to be responsible for the deformation.7,8) In contrast to the abundant works on the deformation in the high temperature range, the number of the experiments so far reported on the deformation at low temperatures is very limited. Wollgarten and his coworkers have conducted microstructure analyses of an icosahedral Al-Pd-Mn deformed by indentation at room temperature and shown that the deformation is not by any dislocation process.9) They have proposed a mechanism based on specimen fragmentation and grain-boundary sliding for the deformation. Texier et al.10,11) and Mompion et al.12,13) have performed deformation of icosahedral Al-Pd-Mn phases at low temperatures under a high pressure and investigated the deformation microstructures by TEM observation. The analysis of the dislocation configurations has revealed that the deformation is controlled by dislocation glide or climb, depending on the sample and temperature.

In the present study, we have performed deformation experiments of Mg-Zn-Y icosahedral quasicrystals at low temperatures under a hydrostatic confining pressure super-imposed to an applied uniaxial stress. This method has been applied previously to the study of low-temperature plasticity of III-V compound semiconductors.12–14) By this method, we have successfully measured, for the first time, the temperature dependence of the yield stress of icosahedral quasicrystal down to room temperature.

2. Experimental Procedures

An alloy with the composition Mg36Zn56Y8 was produced according to the following procedures. First, the appropriate amounts of constituent elements were sealed in a molybdenum ampoule. This was necessary to avoid compositional change during melting by evaporation caused by the fact that at the melting point of yttrium the vapor pressure of magnesium and zinc are extremely high. The ampoule was heated to 1793 K to melt them together and furnace-cooled. Then, the ampoule was heated again to 973 K, which is above the melting point of the alloy, kept at this temperature for 2 h, and water-quenched to minimize the phase separation by peritectic reaction during cooling and to obtain a homogeneous alloy. Finally, the ampoule was annealed at 773 K for 24 h to produce high-quality icosahedral quasicrystal. A part of the alloy ingot was crushed and powdered, and X-ray diffraction measurements were carried out using a rotating anode X-ray generator (Cu Kα, 40 kV, 200 mA) with a graphite monochromator. Figure 1 shows the X-ray diffraction spectrum, which consists entirely of sharp peaks indexable as the F-type icosahedral phase.15) The sample was polycrystalline and transmission electron microscopy revealed that the grain size is of the order of 10 μm.

For compression tests, rectangular specimens of 1.0 × 1.0 × 3.0 mm3 were cut out from the alloy ingot and their surfaces were polished with polishing paper and alumina paste. The uniaxial compression test was carried out using a high-pressure apparatus previously used for the study of low-temperature plasticity of III-V compound semiconductors.12–14) A hydrostatic pressure of 100–500 MPa was applied to the specimen through the confining material by a piston. As the confining material, we used lead, zinc and indium. Then, additional uniaxial stress was applied by the piston to achieve the uniaxial compression. By dummy tests
using NaCl crystals we have evaluated the force expended for the plastic flow of the confining metal and the friction between the piston and cylinder of the high-pressure cell. By subtracting it from the total applied load we have evaluated the uniaxial stress needed for the deformation of the specimen. It has been confirmed in the previous studies\textsuperscript{12–14) that the yield stress evaluated by the above procedures is almost independent of the confining pressure. The high-pressure cell was installed in an electrical furnace and the compression tests were conducted in the temperature range between room temperature and 473 K. For the standard compression tests, the crosshead speed was 0.01 mm/min, which corresponds to the strain-rate of $5 \times 10^{-5}$ s$^{-1}$. For some of the specimens, the strain-rate was changed during the course of straining to evaluate the activation volume. Microstructures of some deformed specimens were observed by transmission electron microscopy (TEM) using a JEOL 200 kV electron microscope.

3. Results and Discussion

Figure 2 shows the stress-strain curves measured at room temperature, where the three curves are for three different specimens. Here, lead was used as the confining material and the confining pressure was 300 MPa. The data in the low stress regime are missing because they could not be evaluated with sufficient accuracy in subtracting the extra force estimated by the dummy test. Each curve shows yielding at around 1.5 GPa. One of the curves shows decrease in the stress immediately after the yielding and terminates. This point corresponds to the fracture of the specimen. The other two curves show linear work hardening after the yielding. We confirmed the plastic deformation of the specimens by measuring the specimen size after the compression experiment. We investigated microstructures of the specimens before and after deformation by TEM and found that the dislocation density increases by the deformation from about $10^6$ cm$^{-2}$ to $5 \times 10^8$ cm$^{-2}$. This fact confirms that the deformation is brought by dislocation process. We found that the confining pressure of 300 MPa is necessary for the specimens to be deformed plastically at room temperature; under the confining pressure smaller than 300 MPa, the specimens often exhibited fracture before yielding.

Figure 3 shows the temperature dependence of the yield stress, where the yield stress values are obtained as the average over several measurements for different specimens. For the Mg-Zn-Y icosahedral quasicrystal, Yoshida and his coworkers\textsuperscript{16) have previously conducted compression experiments at high temperatures and reported the yield stresses of 40–100 MPa in the temperature range of 673–773 K. Compared with those values, the yield stresses in the low temperature region in Fig. 3 are extremely high. In addition,
somewhat irregular temperature dependence is noticed: the yield stress increases rapidly with lowering temperature down to 373 K but it becomes almost constant in the temperature region lower than 373 K. Such an irregular temperature dependence is suggestive of transition between two different deformation mechanisms.

For the Al-Pd-Mn icosahedral quasicrystal, plastic behavior at low temperatures has been investigated by similar techniques to ours. Mompiou and his coworkers\textsuperscript{7,8} have deformed single-crystals of icosahedral Al-Pd-Mn at 573 K under a high pressure and shown that the deformation arises exclusively from dislocation climb. On the other hand, Texier and his coworkers\textsuperscript{10,11} have conducted deformation experiments of polycrystalline Al-Pd-Mn icosahedral quasicrystals in the temperature range between room temperature and 573 K. They have shown the following facts: (1) at room temperature the deformation is mostly brought by dislocation glide but dislocation climb events are also occasionally observed and (2) the frequency of the climb events increases as the deformation temperature is raised. Though no detailed study of the low temperature plasticity has been reported for the icosahedral Mg-Zn-Y, the irregular temperature dependence shown in Fig. 3 may originate in the transition of the dislocation mechanisms between climb and glide. Here, we interpret the origin of the irregular temperature dependence as follows. At high temperatures where atomic diffusion occurs rapidly enough, the critical stress for the climb process is lower than that for the critical stress for the glide one and therefore the former gives the yield stress. With decreasing temperature, the atomic diffusion rate becomes smaller and smaller, resulting in a rapid increase of the critical stress for the climb process. As a consequence, at some critical temperature, the critical stress for the climb process surpasses that for the glide one. Below the critical temperature, the glide process determines the yield stress, which has a more gentle temperature dependence.

We observed by TEM long and straight dislocations along symmetry direction in the specimens deformed at 300 K and 373 K. This fact indicates that the dislocation velocity is governed by kink-pair formation on the glide plane or by jog-pair formation on the climb plane of the straight dislocation segment. By measuring the flow stress change by the strain-rate change during plastic deformation, we evaluated the activation volume to be about 0.17 nm\textsuperscript{3}. This small value of activation volume is consistent with those processes. More detailed analyses of the dislocation microstructures are underway to clarify the deformation mechanism.

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**REFERENCES**