A Large Tensile Elongation Induced by Crystallization in an Amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ Alloy

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An $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ amorphous alloy with the two-stage crystallization process of amorphous $\rightarrow$ amorphous plus fcc-Al $\rightarrow$ Al plus compounds exhibited a large elongation reaching 45% in the temperature range of 450 to 465 K. The temperature range agrees with that where the primary Al particles with a size of about 12 nm precipitate homogeneously at an interparticle spacing of about 6 nm in the amorphous matrix. It is therefore concluded that the appearance of the significant elongation is due to a crystallization-induced elongation phenomenon. The new phenomenon may be interpreted to occur through the sequent processes of inhomogeneous deformation along shear plane, followed by preferential precipitation of Al particles on the shear plane resulting from the deformation-induced increase in temperature and then propagation of the deformation site to other site resulting from the precipitation-induced strengthening in the deformed area. The finding of the crystallization-induced elongation phenomenon may be useful for the production of a consolidated bulk material consisting of the nanoscale Al particles embedded in the amorphous matrix.

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I. Introduction

It has previously been reported that $\text{Al}_{85}\text{Ni}_5\text{Y}_{10}$ ⁽¹⁾ and $\text{Al}_{84}\text{Ni}_{10}\text{Ce}_6$ ⁽²⁾ amorphous alloys exhibiting the glass transition phenomenon before crystallization deform inhomogeneously along the maximum shear plane in the temperature range below T_g , followed by instantaneous fracture along the shear plane without distinct plastic elongation. The further increase in testing temperature to the range between T_g and T_x gives rise to a significant elongation through a viscous flow mechanism⁽³⁾. By utilizing the large viscous flowability in the supercooled liquid region, a consolidation of atomized amorphous powders to a highly dense bulk material with an amorphous structure has been tried for Al-based amorphous alloys exhibiting the glass transition phenomenon⁽⁴⁾. Thus, the amorphous alloys with a distinct glass transition do not exhibit a significant plastic elongation in the temperature range below T_g presumably because of the optimum bonding and packing states of the constituent elements. We have, therefore, sought an Al-based amorphous alloy which exhibits a significant elongation at temperatures well below T_g or T_x , because it is expected that the decrease of the onset temperature for the appearance of the significant elongation may enable the production of a consolidated amorphous bulk without crystalline phase. Most recently, significant elongation exceeding 40% has been detected in Al-Ni-Ce and Al-Ni-Y amorphous alloys in the limited temperature range where the primary fcc-Al phase with a nanoscale particle size is precipitated. This phenomenon seems to be regarded as a crystallization-induced elongation. This paper deals with the ap-

pearance of a significant elongation in the first-stage crystallization temperature range for an $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ amorphous alloy and the reason for its appearance is accounted for.

II. Experimental Procedure

An $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ ingot was prepared by arc melting a mixture of pure Al, Ni and Ce metals in a purified argon atmosphere. A rapidly solidified ribbon with a width of 1.2 mm and a thickness of about 15 μm was prepared by a single roller melt-spinning technique. The rotation speed of copper roller with a diameter of 200 mm was 50 s^{-1} (3000 rpm). The amorphicity of the melt-spun ribbon was examined by X-ray diffractometry and transmission electron microscopy (TEM). The TEM samples were prepared by thinning electrolytically the melt-spun ribbon in a solution of 25% nitric acid and 75% methanol at 243 K. Crystallization temperature (T_x) and heat of crystallization (ΔH_x) were measured by differential scanning calorimetry (DSC) at a heating rate of 0.67 K/s. Tensile strength and elongation were examined at a strain rate of $8.3 \times 10^{-4} \text{ s}^{-1}$ in the temperature range of 300 to 575 K by an Instron-type tensile testing machine. Subsequent to tensile testing, the deformation marking on the sample surface and the fracture surface appearance were examined by optical microscopy and scanning electron microscopy, respectively.

III. Results

Figure 1 shows a bright-field electron micrograph and an electron diffraction pattern of a rapidly solidified $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy. No contrast revealing the precipitation of a crystalline phase is seen in the bright-field image and

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Fig. 1 Bright-field electron micrograph (a) and electron diffraction pattern (b) of a rapidly solidified $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy.

the diffraction pattern shows halo rings typical of an amorphous phase, indicating that the Al-Ni-Ce alloy is composed of an amorphous single phase. Figure 2 shows the DSC curve of the amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy. Two exothermic peaks are seen in the temperature ranges of 405 to 540 and 595 to 630 K. It was confirmed from the results of X-ray diffractometry and transmission electron microscopy that the two exothermic peaks were due to the precipitation of the fcc-Al phase from the amorphous phase and the transformation of the remaining amorphous matrix to Al plus compounds (Al_3Ni and $\text{Al}_{11}\text{Ce}_3$), respectively.

Figure 3 shows the temperature dependence of nominal yield strength (σ_y), nominal ultimate tensile strength (σ_B) and elongation (ϵ_f) of the amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy. σ_y (or σ_B) remains almost constant in the temperature range below 400 K, followed by a rapid decrease at about 410 K, a slight increase in the temperature range of 430 to 450 K, a minimum at about 475 K and then a gradual increase with increasing temperature. The slight increase in σ_y is presumably due to the precipitation of the primary fcc-Al phase. σ_B shows a similar temperature dependence to that for σ_y . That is, σ_B decreases significantly at about 410 K, followed by a minimum at about 450 K and then a maximum at about 525 K. On the other hand, ϵ_f shows a small value of about 1.8% in the temperature range below 400 K, increases drastically to 45% at 465 K and then decreases

Fig. 2 Differential scanning calorimetric curve of an amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy.

Fig. 3 Yield strength (σ_y), ultimate tensile strength (σ_B) and fracture elongation including elastic elongation (ϵ_f) as a function of testing temperature for an amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy.

rapidly with increasing temperature. Here, it is important to point out that the significant increase in ϵ_f takes place in the temperature range where the primary fcc-Al phase precipitates and the slight increase in σ_y is recognized. Furthermore, the good bending ductility was kept for the samples which showed the large elongation, even though the structure changed into a mixed structure of the amorphous and fcc-Al phases.

In order to confirm the microstructure of the samples which exhibited the large elongation, TEM observation was made for the sample subjected to the tensile test at 465 K. As shown in Fig. 4, the fcc-Al phase with a particle size of 10 to 15 nm disperses homogeneously at an interparticle spacing of 4 to 8 nm in the amorphous matrix. The fcc-Al particles appear to have a spherical or an ellipsoidal morphology. The micrograph indicates clearly that the precipitation of the nanoscale fcc-Al particles oc-

Fig. 4 Bright-field electron micrograph (a) and electron diffraction pattern (b) of an amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy subjected to the tensile deformation to 45% in elongation at 465 K.

curred during the tensile deformation, being consistent with the result obtained by DSC. The fracture at temperatures below 525 K takes place along the shear plane and the fracture surface consists of smooth and vein regions, as shown in Fig. 5. The feature of the fracture surface is nearly the same as that⁽⁵⁾ for the ductile amorphous ribbon without any crystalline phase. Thus, there is no distinct difference in the fracture surface appearance caused by the precipitation of the nanoscale fcc-Al particles. The similar fracture surface indicates that the final stage in the deformation and fracture processes occurs through failure of the amorphous matrix.

Figure 6 shows the change in the nominal stress-elongation curves of the $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ amorphous alloy with testing temperature. The stress-elongation curve without appreciable plastic elongation at 300 K is just the same as that for conventional amorphous alloys with good bending ductility, indicating that the deformation occurred inhomogeneously along the shear plane, followed by the instantaneous failure. With increasing testing temperature to 435 K at which the nanoscale fcc-Al particles begin to precipitate, the flow stress shows a maximum and then decreases almost linearly, accompanying the appearance of an elongation of 12%. The increase in testing temperature to 465 K causes a large elongation of 45% without significant increase in flow stress after yielding. Thus, the samples deformed at temperatures where the nanoscale fcc-Al particles precipitate during tensile deformation show a gradual decrease in nominal flow stress with pro-

ceeding deformation, accompanying large elongations. The feature of the stress-elongation curves may be interpreted as follows; the deformation occurs inhomogeneously along the shear plane, leading to a decrease in nominal

Fig. 6 Nominal tensile stress-elongation curves of an amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy subjected to tensile deformation at different temperatures.

Fig. 5 Scanning electron micrographs showing the tensile fracture appearance of an amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy subjected to tensile deformation at 400 K (a), 455 K (b), 525 K (c) and 575 K (d).

stress resulting from the decrease in cross sectional area. The inhomogeneous deformation along the shear plane causes an increase in temperature in the locally deformed region, resulting in a preferential precipitation of the nanoscale fcc-Al particles in the deformed region. The subsequent deformation at the same site is suppressed by the precipitation of the nanoscale fcc-Al particles and hence the deformation region propagates to other undeformed region where the nanoscale fcc-Al particles have not precipitated. The large elongation without significant increase in flow stress for the sample deformed at 465 K seems to originate from the propagation of the deformation region along the longitudinal direction of the sample. The above-described mechanism for the appearance of the significant elongation is also supported from the result that a number of deformation bands are observed along the shear plane which is declined by about 45 degrees to the longitudinal tensile direction, as exemplified in Fig. 7. It is therefore concluded that the significant elongation at 465 K is due to a crystallization-induced elongation.

As shown for the nominal stress-elongation curves at higher temperatures of 500 and 525 K in Fig. 6, the samples consisting of the nanoscale fcc-Al particles embedded in the amorphous matrix exhibit a significant increase in flow stress immediately after yielding, indicating that the nanoscale fcc-Al particles have acted as effective strengthening precipitates to enhance the flow stress. The increase in σ_y and the decrease in ϵ_f at 575 K

are presumably due to the precipitation of Al_3Ni and $\text{Al}_{11}\text{Ce}_3$ from the remaining amorphous phase. The appearance of the crystallization-induced elongation without a significant increase in flow stress in the temperature range well below the precipitation temperature of the compounds is very important because of the possibility that the ductile consolidated bulks consisting of amorphous and fcc-Al phases are obtained by utilizing the large crystallization-induced deformability. The consolidation of the amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy and the characterization of the consolidated bulks are in progress, in comparison with the bulks obtained by utilizing the large viscous flowability caused by the transition to a supercooled liquid for amorphous Al-Ni-Ln (Ln=Y, La, Ce, Mm) alloys with the distinct glass transition phenomenon.

IV. Summary

Mechanical properties and microstructures as a function of testing temperature were examined for an $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ amorphous alloy exhibiting a distinct two-stage crystallization process consisting of amorphous $\rightarrow$ amorphous plus fcc-Al $\rightarrow$ fcc-Al plus compounds (Al_3Ni and $\text{Al}_{11}\text{Ce}_3$). When the sample is deformed at about 465 K where the nanoscale fcc-Al particles precipitate in the amorphous matrix, a large elongation reaching about 45% without significant increase in flow stress is obtained, accompanying the appearance of distinct deformation markings along the shear plane. The mixed phase alloy subjected to the tensile deformation up to 45% in elongation at about 465 K keeps good bending ductility at room temperature. The appearance of the large elongation in the limited temperature range was attributed to the crystallization-induced elongation phenomenon. The new phenomenon is presumed to occur through the following processes of the preferential precipitation along the shear plane resulting from the deformation-induced increase in temperature, followed by the increase in the flow stress at the precipitation site, and then the propagation of the deformation region to other region along the tensile direction of the sample. The large elongation in the temperature range well below the precipitation temperature of the compounds is very important for the consolidation of the amorphous powder into a bulk form with good ductility consisting of amorphous and fcc-Al phases.

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Fig. 7 Optical interference micrographs revealing the deformation markings on the sample surface for an amorphous $\text{Al}_{88}\text{Ni}_{10}\text{Ce}_2$ alloy subjected to the tensile deformation to 45% in elongation at 465 K.