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Influence of External Stress on Discontinuous Precipitation Behavior in a Cu-Ag Alloy

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Abstract

The influence of an applied stress on discontinuous precipitation (DP) has been investigated for a Cu-5 wt. pct. Ag alloy aged at 573 K. A tensile stress enhances the growth of DP cells in both the loading direction (LD) and transverse direction (TD), but the cell growth rate in the TD, v_{CT}, is faster than that in the LD, v_{CL}. A compressive stress suppresses the cell growth in the TD, but does not significantly influence it in the LD. The tensile or compressive stress tends to produce discontinuous silver precipitates elongated in a $<110>_{\alpha}$ direction of the copper matrix in a DP cell, nearly perpendicular to or parallel to the LD. This result, along with the dependence of the cell growth rate on the sense of the applied stress, can be understood through the interaction energy between the external stress and the misfit strains of silver precipitates. An analysis of length-change measurement results has enabled estimation of the ratio of the growth rate of silver precipitates in the TD, v_{PT}, to that in the LD, v_{PL}, under tension or compression. The estimated values of v_{PT}/ v_{PL} are in good agreement with the values of v_{CT}/ v_{CL}, experimentally obtained, indicating that the anisotropy of the cell growth rate is determined by the growth behavior of silver precipitates.

I. INTRODUCTION

In 1964, Sulonen[1, 2] has proposed that the driving force for reaction front migration during discontinuous precipitation (DP) stems from the coherency stress in the matrix due to the change in composition across the reaction front. Accordingly, it has been substantiated that an applied stress has a profound influence on the growth rate of DP cells in six binary alloys, namely Cu-Ag, Cu-Mg, Cu-Cd, Zn-Cu, Ag-Cu and Pb-Sn. For the six alloys, the growth rates of DP cells at grain boundaries aligned parallel and transverse to the loading direction are different from each other. Hillert[3] has provided a quantitative treatment of the experimental results obtained by Sulonen, based on the elastic interaction between the misfit stress field around the solute atoms ahead of the reaction front and applied tensile stress. Chung *et al*.[4] have proposed a quantitative analysis of the effect of external stress on the velocity of the reaction front aligned parallel and transverse to the loading direction.

In a previous study,[5] Monzen *et al.* have examined the effects of an applied compressive or tensile stress on the DP behavior in a Cu-2.1 wt. pct. Be alloy aged at 573 K. The DP cell consists of lamellae of the equilibrium γ phase (CuBe intermetallic) and solute-depleted α phase (copper matrix). They have found that the growth of DP cells under the compressive stress occurs more rapidly than that under the tensile stress, and the growth rates in the loading and the transverse directions are identical, different from the previous observations.[1, 2, 4, 6] These results were in disagreement with the predictions from the analysis result by Chung *et al*.[4] In addition, length-change measurements have been undertaken to estimate the average misfit strains along the loading direction (LD) and transverse direction (TD), caused by the negative misfit strains between the α and γ phases.[7] The dependences of the estimated misfit strains on the sense (tension or compression) of the applied stress and the measured directions have revealed that specific γ variants among crystallographically equivalent ones are formed, depending on the sense of the applied stress. This result, along with the effect of the sense of the applied stress on the cell growth rate, can be well explained in terms of the interaction energy due to the presence of negative misfit strains of the γ phase between the external stress and γ precipitate.[8, 9]

In this work, as an extension of the previous study, the effects of an applied tensile or compressive stress on the growth rate and morphology of DP product will be investigated in a Cu-5 wt. pct. Ag alloy aged at 573 K. The DP cell consists of lamellae of the rod-shaped silver-rich β phase and solute-depleted α phase.[10, 11] It has been found that not only the cell growth rate but also the growth direction of discontinuous silver precipitates depends on the sense of the applied stress and the cell growth direction. The dependences of the cell growth rate and the morphology of silver precipitates on the sense of the applied stress can be explained by the interaction energy between the external stress and the misfit strains of silver precipitates.[12] Moreover, length-change measurements have been performed to estimate the average misfit strains along the LD and TD, due to the positive misfit strains of silver precipitates. It will be shown that the anisotropy of the cell growth rate is well represented by the growth behavior of silver precipitates derived from an analysis of the length-change measurement results.

II. EXPERIMENTAL

Cu-5 wt. pct. Ag alloy ingots were prepared by melting 99.99 wt. pct. Ag and 99.99 wt. pct. Cu. The alloy ingots were homogenized at 1073 K for 24 hours in a vacuum. Specimen pieces were cut from the ingots and cold-rolled to 50 percent reduction in thickness. For tensile aging, the specimens had a cross-section of $3\,\text{mm} \times 6\,\text{mm}$ and a gage length of 20 mm. For compressive aging, the specimens had the same cross-section but a length of 6 mm. All the specimens were solution-treated at 1053 K for 1 hour in a vacuum and quenched into water. Aging was carried out at 573 K for various times either under an applied stress of 20 MPa (stress aging) or under no stress (free aging) in a vacuum. The applied stress of 20 MPa is about one third of the yield strength of the solution-treated specimen at 573 K. The average grain size after the solution treatment was about 30μm.

From an as-rolled Cu-5 wt. pct. Ag alloy plate after homogenizing the alloy ingot at 1073 K for 24 hours, a sheet-shaped bicrystal, 2-mm thick, was grown in a high-purity graphite mold by the Bridgman technique. The grain boundary in the bicrystal was of random type and the boundary misorientation was 52 deg. The bicrystal was spark-cut into bicrystal pieces of 2 mm×5 mm×20 mm or 2 mm×5 mm×5 mm. The bicrystals were solution-treated at 1053 K for 1 hour in a vacuum, quenched into water and then aged at 573 K under the applied stress of 20 MPa in a vacuum. A chemical analysis showed that the aged specimens contained 4.5 wt. pct. Ag. The decrease in amount of silver in copper from 5 to 4.5 wt. pct. was caused by melting the as-rolled Cu-5 wt. pct. Ag alloy plate.

Length changes, ε_T, on aging were examined by measuring, with a micrometer, the distance between two scribed marks, about 5 mm and 10 mm apart for the compressive-stress-aged and tensile-stress-aged polycrystal specimens, respectively. The length change is defined as $\varepsilon_T=(l-l_0)/l_0$, where l_0 and l are the length between the two marks before and after aging at 573 K for a time, respectively. The measurement accuracy of length change is in the order of 10^{-5} in strain. An X-ray analysis was performed to measure the lattice constants of the solution-treated and aged specimens.

After aging, optical microscopic observations were carried out to measure the width of DP cells. Transmission electron microscopy (TEM) was performed using a Hitachi H-9000NAR and a JEOL 2010FEF microscope at operating voltages of 300 and 200 kV. Thin foils for TEM observations were prepared using a twin-jet polishing method with a solution of 67 vol. pct. methanol and 33 vol. pct. nitric acid at 243 K and 6.5 V after slicing the aged specimens with a spark cutter.

III. RESULTS

A. *Growth of DP cells*

Figures 1(a), 1(b) and 1(c) depict optical microscopy images for the Cu-5 wt. pct. Ag specimens, free-aged, tensile-stress-aged and compressive-stress-aged at 573 K for 1 hour. DP cells under no stress grow randomly to all directions. In the tensile-stress-aged specimen, the width of cells in the transverse direction (TD) is larger than that in the loading direction (LD), but the situation for the compressive-stress-aged-specimen is reversed. The former is in agreement with the observation by Sulonen[2] for a Cu-5 wt. pct. Ag alloy aged at 773 K for 30 minutes under tension. Figure 2 presents the cell width, *w*, against aging time, *t*, for the specimens, free-aged (FA), compressive-stress-aged (CSA) and tensile-stress-aged (TSA) at 573 K. About 50 DP cells were examined for each data point. A linear relationship is observed between *w* and *t* for these specimens. The growth of DP cells along both the LD and TD in the TSA specimen occurs more rapidly than that in the FA specimen, but the cell growth along the TD is faster than that along the LD. In addition, the cell growth along the TD in the CSA specimen is suppressed but it along the LD is essentially unaffected. It is also seen that the applied stress has no influence on the incubation period to initiate DP (i.e. the intercept on the abscissa at w=0). This is in agreement with the result previously obtained for a Cu-2.1 wt. pct. Be alloy aged at 573 K.[5] The reason why the incubation period is unaffected by the applied stress has already been discussed in the previous study.[5]

In the TSA bicrystal specimens aged up to 30 hours also, the growth of DP cells along both the LD for the grain boundary aligned perpendicular to the LD and the TD for the same aligned parallel to the LD was accelerated, and the cell growth along the TD occurred more rapidly than that along the LD. The growth along the TD in the CSA specimen was suppressed and along the LD it was essentially unaffected. The external stress was 20MPa, identical to that applied to the Cu-Ag polycrystal specimens. In addition, the FA, TSA and CSA bicrystal specimens showed the absence of stress effect on the incubation period to initiate DP. However, the cell growth rates and the incubation period for the bicrystal specimens were slower and longer than those for the polycrystal specimens, since the silver concentration in the Cu-4.5 wt. pct. Ag bicrystal specimen was lower than that in the Cu-5 wt. pct. Ag polycrystal specimen.

It is generally accepted that in-grain precipitates affect the DP kinetics[13]. When single crystals of Cu alloys having about 5 wt. pct. Ag are aged at temperatures between about 673 and 873 K, disk-shaped aggregates, consisting of rod-shaped silver precipitates and silver-depleted copper matrix, are produced in the $\{100\}_\alpha$ planes[14, 15]. However, no precipitation occurred within grain interiors during aging at 573 K up to 20 or 30 hours, after which the surface of the TSA polycrystal specimen or the FA and CSA polycrystal specimens was occupied by DP cells. Also, no precipitates were observed in the copper matrix of the bicrystal specimens after aging up to 30 hours.

Explanations of the results of Sulonen[1, 2] on the effect of applied stress on DP have been put forward by Sulonen[1, 2] and Hillert.[3] When DP occurs in an elastically isotropic solid under an external stress, σ, and with a coherency strain, δ, in the solute diffusion zone adjacent to a grain boundary, the elastic strain energy, ΔG, in the coherent zone at the grain boundary oriented transversely to the LD is given as[4]

$$\Delta G = \frac{E}{1-\nu}\delta^2 - \frac{2\nu}{1-\nu}\delta\sigma , \qquad (1)$$

where E is the Young's modulus and ν is the Poisson's ratio. For the grain boundary aligned parallel to the LD, the driving force for moving it is written as

$$\Delta G = \frac{E}{1-\nu}\delta^2 + \delta\sigma . \qquad (2)$$

It can be noted in equations (1) and (2) that, when ν=1/3 is used, the growth rate of DP cells in the TD under tensile or compressive stress should be identical to that in the LD under compressive or tensile stress. Since the sign of δ is plus in the present work,[12] equation (2) predicts that the cell growth in the TD is promoted under tension and suppressed under compression. This prediction is in agreement with the result shown in Figure 2. Moreover, it may be expected from equation (1) that the cell growth rate in the LD under tension or compression is slower or faster than that under no stress. This is in conflict with the result of Figure 2 that the growth rate in the LD under tension is faster than that under no stress and the growth rate in the LD under compression is nearly identical to that under no stress.

B. *Precipitation morphology*

The occurrence of DP reactions growing in two directions from one boundary in the FA, TSA and CSA specimens was always observed. Double-seam DP morphology took place as a result of the growth in opposite directions from the initial grain-boundary configuration.[10, 11] TEM observations of various DP cells in the FA specimen revealed that silver precipitates in cells had an elongated shape along a $<110>_\alpha$ direction of the silver-depleted copper matrix. This direction is in agreement with the elongated $<110>_\alpha$ direction of rod-shaped silver precipitates in disk-shaped aggregates parallel to $\{100\}_\alpha$ planes in Cu-5.7 wt. pct. Ag single crystals.[15] The discontinuous silver precipitates exhibited a cube-on-cube orientation relationship to the copper matrix, in accordance with the previous studies on Cu-Ag alloys.[16, 17] In the FA specimen, rod-shaped silver precipitates behind an advancing grain-boundary grew in a $<110>_\alpha$ direction nearly perpendicular to the grain boundary among the six possible $<110>_\alpha$ directions. This was found by TEM observations from various directions of the silver precipitates in several DP cells.

Figures 3(a) and 3(b) depict TEM images of discontinuous silver precipitates after migration of the same grain-boundary aligned parallel to and perpendicular to the LD for the

Cu-4.5 wt. pct. Ag bicrystal, tensile-stress-aged at 573 K for 2 hours. Figure 4 is the stereographic projection corresponding to Figure 3(a). In Figure 3(a), the silver precipitates are elongated in a direction nearly perpendicular to the grain boundary. The TEM observation from various directions showed that the elongated direction was parallel to the $[110]_\alpha$ direction of grain A. The $[110]_\alpha$ direction makes the smallest angle of about 30 deg. to the boundary normal among the six possible $\langle 110 \rangle_\alpha$ directions. It should be noted from Figures 3(b) and 4 that the silver precipitates initially grow along the $[0\bar{1}1]_\alpha$ direction of grain A which makes the smallest angle of about 30 deg. to the boundary normal, but their growth direction is changed into the $[\bar{1}10]_\alpha$ direction nearly perpendicular to the LD. In the CSA bicrystal, when the grain boundary aligned parallel to the LD moved toward grain B, the silver precipitates were initially elongated in the $[110]_\alpha$ direction of grain A, but their growth direction was changed into the $[011]_\alpha$ direction of grain A relatively close to the LD. For the grain boundary which was oriented transversely to the LD and moved toward grain B, the silver precipitates grew in the $[0\bar{1}1]_\alpha$ direction of grain A, relatively parallel to the boundary normal or LD.

The change in growth direction was often observed in the TSA and CSA polycrystal specimens, irrespective of the growth direction of DP cells. In the TSA and CSA specimens, the initial growth direction of silver precipitates in several DP cells examined was a $\langle 110 \rangle_\alpha$ direction nearly perpendicular to the grain boundary. It is evident that the applied stress has no influence on the initial growth direction of silver precipitates. The change in the growth direction of silver precipitates in the TSA or CSA specimen was toward $\langle 110 \rangle_\alpha$ nearly perpendicular or parallel to the LD.

C. *Length change of specimens*

Figure 5 shows the length change, ε_T, along the LD and TD, plotted as a function of aging time, *t*, for the FA, CSA and TSA specimens on aging at 573 K for various times up to 80 hours (2.88×10^5 seconds). In the early stage of aging up to 30 minutes (1.8×10^3 seconds), length change along the LD and TD for the FA, CSA and TSA specimens shows no essential change. DP reactions began to occur after aging for 30 minutes and proceeded until the surface of the TSA specimen or the FA and CSA specimens was covered with DP cells after 20 or 30 hours (7.2×10^4 or 1.08×10^5 seconds). After aging for 20 hours, no precipitates were observed within the grain interiors. As the amount of DP cells increased, length change along the LD or TD for the TSA specimen initially exhibited a slight increase or a rapid decrease and then a plateau behaviour after 20 hours, whereas it along the LD or TD for the CSA specimen rapidly decreased or slightly increased up to 30 hours and became constant. The FA specimen shows a decrease in length change and then a constant value after 30 hours. Similar to the previous observation,[5] there existed no anisotropy in length change of the FA specimen. It should be noted that length change along the LD for the TSA specimen exhibits no change after aging for 30 minutes, a slight increase up to 20 hours and no change between 20 and 80 hours. The result of microhardness tests revealed that the Vickers hardness of grain interiors was constant during aging up to 20 hours, but smaller than the hardness of DP cells. These results indicate that the creep strain due to dislocation motion does not essentially contribute to the length change.

When the specimen surface is filled up with DP cells, the specimen length change, ε_{T}, along a direction is given as functions of the average misfit strain, ε_{a}, in the direction, caused by the misfit strains of discontinuous precipitates,[12] the volume fraction, f, of the precipitates, and the dimensional change, ε_{l}, due to the loss of silver solute atoms from the solid solution, by the following equation:[5]

$$\varepsilon_{\mathrm{T}} = f\varepsilon_a + (1 - f)\varepsilon_{\mathrm{l}}, \qquad (3)$$

where $\varepsilon_{\mathrm{l}} = (a - a_0)/a_0$. Here a_0 and a are the lattice parameters of specimens before and after aging.

The average misfit strains, $\varepsilon_{\mathrm{aL}}$ and $\varepsilon_{\mathrm{aT}}$, along the LD and TD will be estimated for the

FA, TSA and CSA specimens. The value of f = 0.043 was determined by applying the values of a_0=0.3631nm and a=0.3615nm after aging for 80 hours to the experimental data regarding the dependence of the lattice parameter on silver concentration.[18] The values of ε_{aL} and ε_{aT} for the TSA, CSA and FA specimens, estimated from the values of ε_T in Figure 5, f and ε_l, are summarized in Table I. In the FA specimen, silver precipitates elongated in each $<110>_\alpha$ direction are equally present in the copper matrix, and thus there exists no anisotropy in length change. In this case, the value of ε_a can be calculated as 0.085 from $\varepsilon_a=(\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33})/3$, [5, 7] where ε_{33}=0.015 and $\varepsilon_{11}=\varepsilon_{22}$=0.12 are the misfit strains along the elongated $<110>_\alpha$ direction of a rod-shaped silver precipitate and along the direction normal to the elongated direction.[12] The calculated value is in good agreement with the experimentally obtained value of ε_a=0.083 in Table I. For the TSA specimen, $0.015< \varepsilon_{aT}=0.076< \varepsilon_{aL}=0.095< 0.12$, and, for the CSA specimen, $0.015 < \varepsilon_{aL}=0.078 < \varepsilon_{aT}=0.096< 0.12$. This means that tensile or compressive stress is apt to produce the rod-shaped silver precipitates elongated in a $<110>_\alpha$ direction close to right angles to the LD or close to the LD. This is coincident with the observed morphology of silver precipitates under tension (Figure 3) and compression.

IV. DISCUSSION

As described in Section III-A, the results shown in Figure 2 that the cell growth rate along the LD under tensile stress is faster than that under no stress and the growth rate along the LD under compressive stress is nearly identical to that under no stress cannot be interpreted using equations (1) and (2). It can be understood that the origin of the effects of the sense of the applied stress on the cell growth rate (Figure 2), the morphology of silver precipitates (Figure 3) and the average misfit strains in the LD and TD (Table I) arises from the interaction energy due to the presence of positive misfit strain, ε_{ij}, (stress-free transformation strain) between a silver precipitate and an external stress, σ_{ij}. The interaction energy implies the work done by the applied stress during the growth of discontinuous silver precipitates. The interaction energy, ΔE, per unit volume of the silver precipitate is calculated as[8, 9]

$$\Delta E = -\sigma_{ij}\varepsilon_{ij}. \tag{5}$$

It may be expected from this equation that the growth of silver precipitates, namely DP cells is promoted by applied tensile stress and, as a result, the growth of cells under tensile stress is easier than that under compressive stress. This prediction is in agreement with the result shown in Figure 2. Also, equation (5) predicts that the rod-shaped silver precipitates elongated in a <110> direction nearly perpendicular to or parallel to the LD are produced under tension or compression, since the misfit strains along the elongated $<110>_{\alpha}$ direction of a rod-shaped silver precipitate and along the direction normal to the elongated direction are ε_{33}=0.015 and ε_{11}=ε_{22}=0.12.[12] This also is coincident with the observed morphology of silver precipitates under tension (Figure 3) and compression, and the dependence of the average misfit strains in the LD and TD on the sense of the applied stress in Table I.

Using the misfit strains, ε_{11}=ε_{22}=0.12 and ε_{33}=0.015, of the rod-shaped silver precipitate[12] and the values of ε_{aL} and ε_{aT} in Table I, the angles, ϕ_{TT} and ϕ_{TC}, between the average elongated direction of silver precipitates and the TD for the TSA and CSA specimens were estimated as ϕ_{TT} =29 deg. and ϕ_{TC}=60 deg. Then the ratio of the average growth velocity of silver precipitates along the TD, v_{PT}, to that along the LD, v_{PL}, can be calculated for the TSA and CSA specimens. The calculated values of v_{PT}/v_{PL} for the TSA and CSA specimens are listed in Table II, together with the ratio of the cell growth rate, v_{CT}, along the TD to that, v_{CL}, along the LD, experimentally obtained (Figure 2). Interestingly, the agreement between the values of v_{PT}/v_{PL} and v_{CT}/v_{CL} is excellent for the TSA and CSA specimens. Thus it is concluded that the anisotropy of the cell growth rate is determined by the effect of the applied stress on the growth morphology of discontinuous silver precipitates.

V. CONCLUSIONS

An investigation of the effect of an applied stress on discontinuous precipitation (DP) behavior in a Cu-5 wt. pct. Ag alloy aged at 573 K has yielded the following conclusions:

1. Application of a tensile stress promotes the growth of DP cells in both the loading direction (LD) and transverse direction (TD) but the cell growth along the TD occurs more rapidly than that along the LD. A compressive stress does not significantly affect the cell growth rate along the LD but decreases it along the TD. The incubation time to initiate DP is unaffected by the applied stress.

2. The applied stress has no influence on the initial growth direction of discontinuous rod-shaped silver precipitates in a DP cell, which is a $<110>_{\alpha}$ direction nearly perpendicular to the advancing grain-boundary. However, the initial growth direction tends to be changed into a $<110>_{\alpha}$ direction nearly perpendicular and parallel to the LD during aging under tension and compression, respectively.

3. The dependences of the cell growth rate and the observed morphology of silver precipitates on the sense of the applied stress can be understood through the interaction energy due to the presence of positive misfit strains between the applied stress and silver precipitate.

4. The result that the tensile or compressive stress is apt to produce the silver precipitates elongated in a $<110>_{\alpha}$ direction nearly perpendicular or parallel to the LD is supported by the dependence of the average misfit strains in the TD and LD, estimated from length-change measurements, on the sense of the applied stress. The ratio of the average growth rate of silver precipitates in the TD to that in the LD under tension or compression, estimated from length-change measurement results, is in good accord with the ratio of the cell growth rate in the TD to that in the LD. This shows that the growth behavior of silver precipitates under the applied stress determines the dependence of the cell growth rate on the growth direction.

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Figure and Table Captions

Fig. 1 Light micrographs of (a) free-aged, (b) tensile-stress-aged and (c) compressive-stress-aged specimens. Aging was performed at 573 K for 1 hour. The arrows in (b) and (c) indicate the loading direction.

Fig. 2 Variation in the width of discontinuous precipitation cells during free aging, tensile-stress aging and compressive-stress aging at 573 K. LD=Loading Direction, TD=Transverse Direction.

Fig. 3 (a) TEM image of rod-shaped silver precipitates in cells after migration of the same grain-boundary, aligned (a) parallel to and (b) perpendicular to the loading direction (LD), in the bicrystal specimen, tensile-stress aged at 573 K for 2 hours. RF=Reaction Front.

Fig. 4 Stereographic projection corresponding to Figure 3(a). $<110>_{\alpha}$ directions of grain A and grain B are indicated.

Fig. 5 Variation in the specimen length-change during free aging, tensile-stress aging and compressive-stress aging at 573 K.

Table I Average misfit strains along the loading direction and transverse direction, ε_{aL} and ε_{aT}, obtained by length-change measurements, for the specimens, tensile-stress-aged (TSA), compressive-stress-aged (CSA) and free-aged (FA) at 573 K.

Table II Ratio of the growth rate of discontinuous silver precipitates, v_{PT}, or discontinuous precipitation cells, v_{CT}, in the transverse direction to that of silver precipitates, v_{PL}, or cells, v_{CL}, in the loading direction, calculated using the values of ε_{aL} and ε_{aT} in Table I and obtained experimentally from Figure 2, respectively, for the specimens, tensile-stress-aged (TSA) and compressive-stress-aged (CSA) at 573 K.

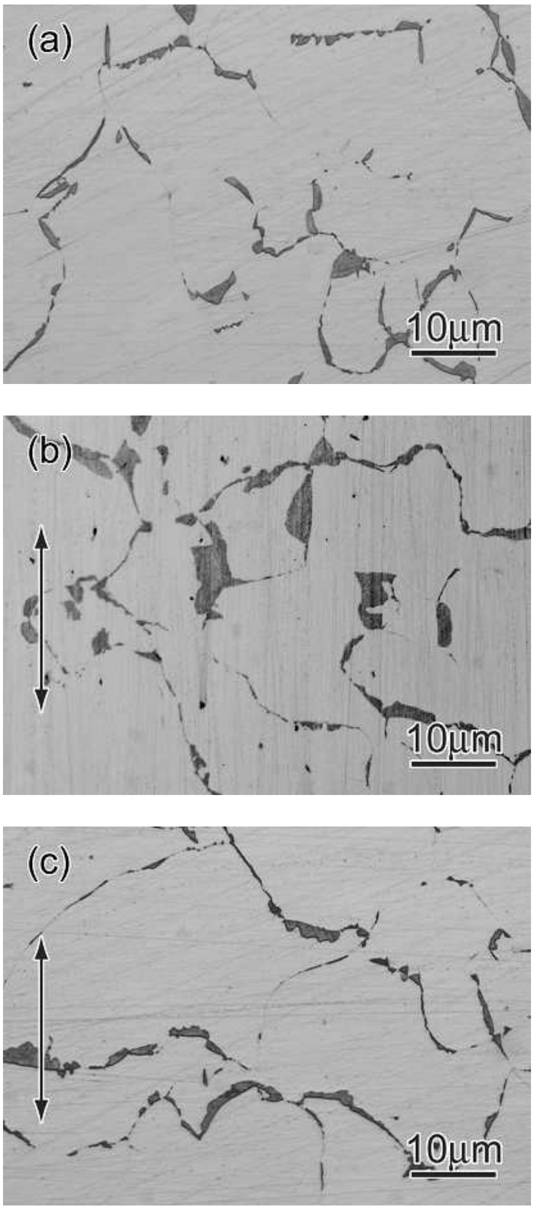

Fig. 1 Light micrographs of (a) free-aged, (b) tensile-stress-aged and (c) compressive-stress-aged specimens. Aging was performed at 573 K for 1 hour. The arrows in (b) and (c) indicate the loading direction.

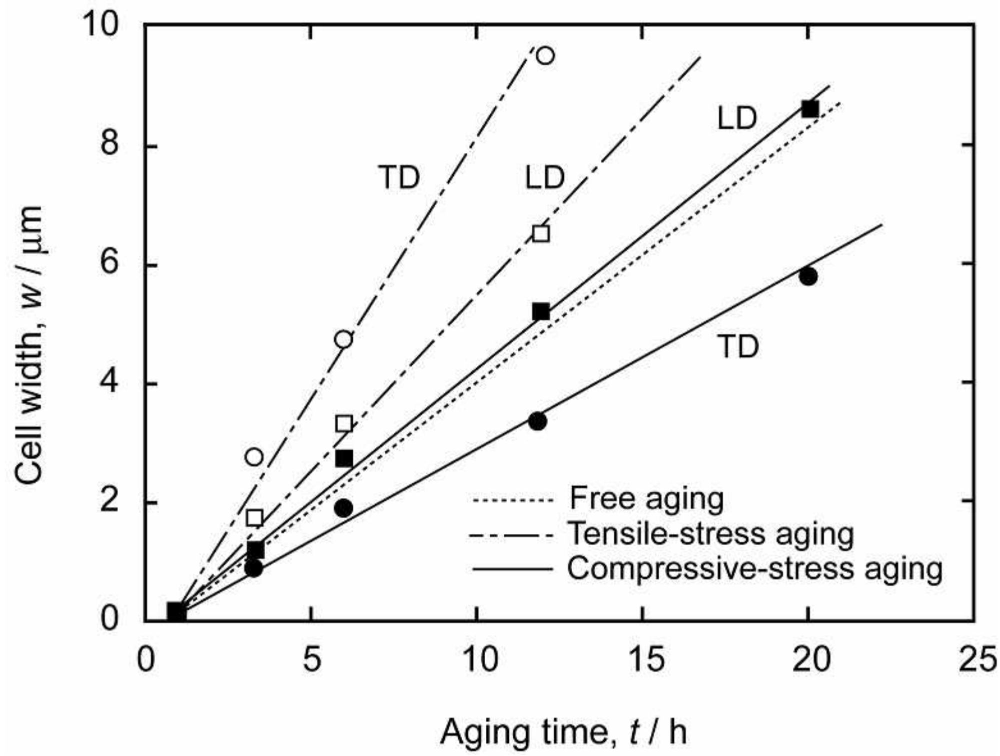

Fig. 2 Variation in the width of discontinuous precipitation cells during free aging, tensile-stress aging and compressive-stress aging at 573 K. LD=Loading Direction, TD=Transverse Direction.

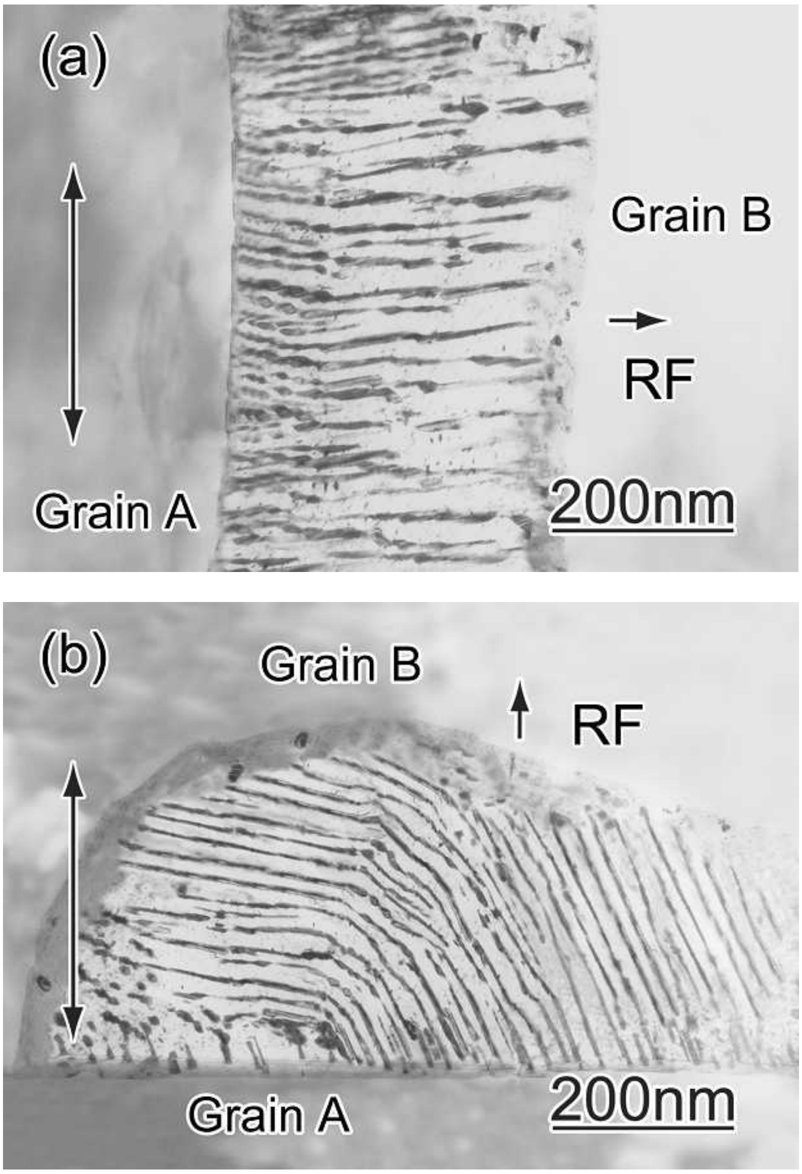

Fig. 3 (a) TEM image of rod-shaped silver precipitates in cells after movement of the same grain-boundary, aligned (a) parallel to and (b) perpendicular to the loading direction (LD), in the bicrystal specimen, tensile-stress aged at 573 K for 2 hours. RF=Reaction Front.

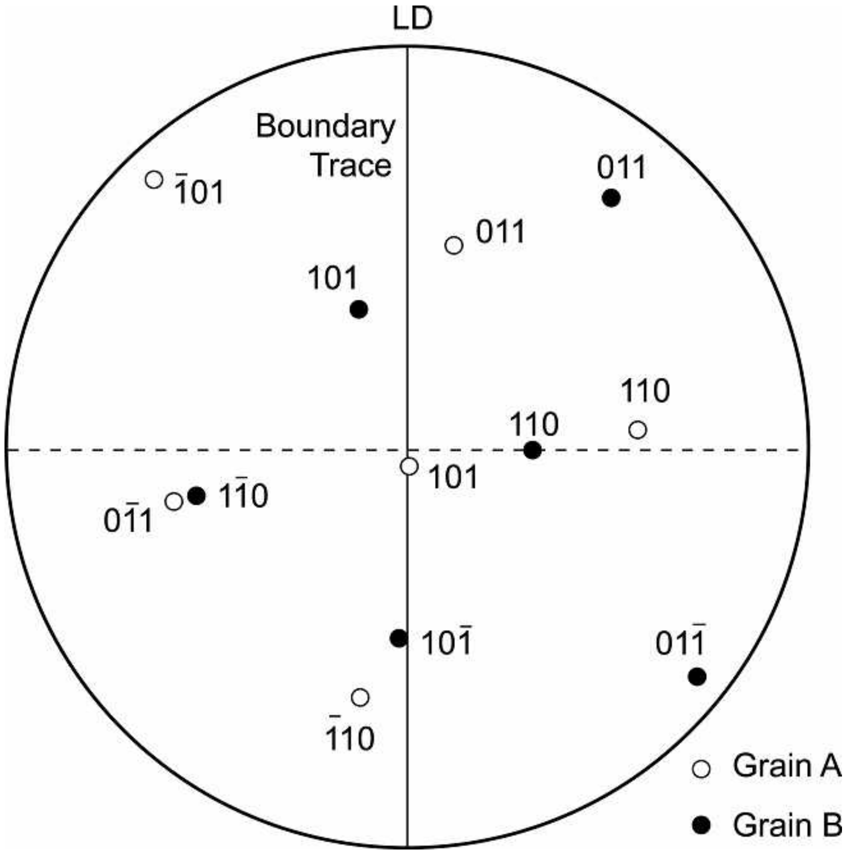

Fig. 4 Stereographic projection corresponding to Figure 3(a). <110>$_\alpha$ directions of grain A and grain B are indicated.

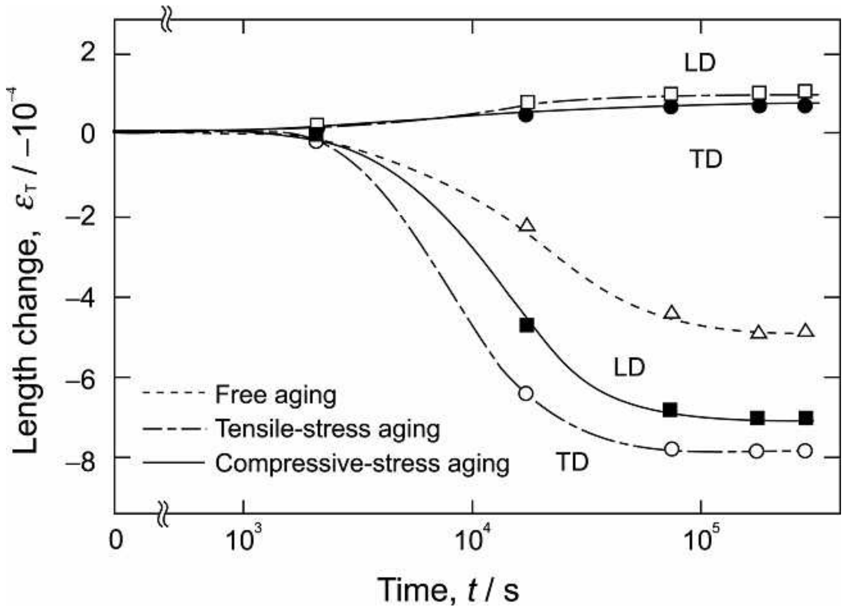

Fig. 5 Variation in the specimen length-change during free aging, tensile-stress aging and compressive-stress aging at 573 K.

Table I Average misfit strains along the loading direction and transverse direction, ε_{aL} and ε_{aT}, obtained by length-change measurements, for the specimens, tensile-stress-aged (TSA), compressive-stress-aged (CSA) and free-aged (FA) at 573 K.

Specimen	ε_{aL}	ε_{aT}
TSA	0.095	0.076
CSA	0.078	0.096
FA	0.083	

Table II Ratio of the growth rate of discontinuous silver precipitates, v_{PT}, or discontinuous precipitation cells, v_{CT}, in the transverse direction to that of silver precipitates, v_{PL}, or cells, v_{CL}, in the loading direction, calculated using the values of ε_{aL} and ε_{aT} in Table I and obtained experimentally from Figure 2, respectively, for the specimens, tensile-stress-aged (TSA) and compressive-stress-aged (CSA) at 573 K.

Specimen	v_{PT}/v_{PL}	v_{CT}/v_{CL}
TSA	1.8	1.7
CSA	0.6	0.6