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Ryoichi MONZEN[1], Tomoyuki HASEGAWA[2] and Chihiro WATANABE[3]

[1] Corresponding author, Division of Innovative Technology and Science, Kanazawa University, Kakuma-machi, Kanazawa 920-1192

TEL: +81-76-234-4678, FAX: +81-76-264-6495

Email: monzen@t.kanazawa-u.ac.jp

[2] Division of Mechanical Science and Engineering, Kanazawa University, Kakuma-machi, Kanazawa 920-1192

TEL: +81-76-234-4678, FAX: +81-76-264-6495

Email: hasegawa@metal.ms.t.kanazawa-u.ac.jp

[3] Division of Innovative Technology and Science, Kanazawa University, Kakuma-machi, Kanazawa 920-1192

TEL: +81-76-234-4680, FAX: +81-76-264-6495

Email: chihiro@t.kanazawa-u.ac.jp

Abstract

The influence of prior cold work (90% reduction) on the length change and precipitation behaviour of a Cu-1.8wt%Be-0.2wt%Co alloy aged at 320 ºC up to 350 h has been investigated. The alloy gradually expands to a maximum and then contracts during ageing. The maximum expansion is attributable to both the expansion due to loss of the Be solute atoms and the contraction due to precipitation of the γ'_I, γ_I, γ_m and γ' phases. The subsequent contraction results from the decrease in amounts of the γ'_I and γ_m phases and the increase in amount of the γ' phase. The new-found γ_m phase, consisting of alternate Be and Cu matrix layers parallel to the matrix $\{001\}_\alpha$, is body-centred monoclinic with a=b=0.263 nm and c=0.279 nm and a=83°, and aligns with the matrix according to the Bain orientation relationship. The Guinier-Preston (GP) zone transforms continuously to the γ_m or γ_I phase via γ" and γ'_I. The transformation from the GP zone to γ' via γ", γ'_I and γ_I is retarded in comparison with that for the undeformed alloy.

Key words: Cu-Be-Co alloy, dimensional change, precipitation behaviour, γ_m phase, plastic deformation, misfit

1. Introduction

The precipitation sequence from α supersaturated solid solution in Cu-Be alloys has been reported by many investigators and summarized as follows [1–4]: Guinier-Preston (GP) zone → γ” → γ’ → γ. Recently, however, high-resolution transmission electron microscopy (HRTEM) of precipitated phases in Cu-0.9wt%Be alloy single crystals containing only the GP zones on the $(001)_\alpha$ plane [5] has revealed that the phases follow a complicated GP zone → γ” → γ'_I → γ_I + γ’ → γ sequence with increasing ageing time [6]. The disc-shaped GP zones consist of monolayers of Be atoms on the $\{100\}_\alpha$ planes and transform continuously to the γ_I phase via γ” and γ'_I. These metastable phases are composed of alternative Be and Cu matrix layers parallel to $\{100\}_\alpha$. The metastable γ’ phase heterogeneously precipitates on the γ_I phase and transforms successively to the equilibrium γ phase. Table 1 lists the lattice parameter values of these phases.

Moreover, we have determined the misfit strains of GP zones [5] and γ”, γ'_I, γ’ and γ precipitates [7] from measurements of the length change and the lattice parameter on ageing using the Cu-0.9wt%Be single crystals containing only the GP zones on the $(001)_\alpha$ plane, as shown in Table 2. Here, ε_{11} (=ε_{22}) and ε_{33} are the misfit strains in directions parallel and perpendicular to the plate plane of the GP zone. In addition, length-change measurements have been performed for Cu-1.8wt%Be-0.2wt%Co alloy polycrystals aged at 320 and 500°C after a solution treatment at 820°C [7]. On ageing at 320°C, the alloy contracted with precipitation of the γ’ phase and then slightly expanded with precipitation of the γ phase. Ageing at 500°C produced a gradual decrease in length change with growing discontinuous precipitation cells, consisting of the plate-shaped γ precipitates and the Cu matrix. The length-change behaviour is well elucidated by an analysis using the estimated misfit strains of the phases in Table 2 and the lattice parameters of the Cu matrix on ageing.

In this letter, we will investigate the length change of the Cu-1.8wt%Be-0.2wt%Co alloy on ageing at 320ºC after solutionizing at 820°C and subsequent cold-rolling by 90%

reduction, in conjunction with the precipitation behaviour. The heavily cold-rolled alloy has gradually expanded and successively contracted during ageing, different from the result of the rolling-free Cu-Be-Co alloy [7]. We have found, by HRTEM, more complicated precipitation processes in the cold-rolled alloy than in the rolling-free alloy, and a new-precipitated phase called γ_m, as will be shown later. Comparison between the length changes experimentally obtained and those theoretically calculated using the lattice misfits in Table 2 has revealed that the gradual expansion and successive contraction of the cold-rolled alloy during ageing is a consequence of the combined dimensional changes based on the complicated precipitation processes and the depletion of Be solute atoms in the Cu matrix. Previous to this work, Miki *et al*. [8] reported that such a gradual expansion of a heavily deformed Cu-Be-Co alloy during ageing at 320ºC would be caused by precipitation of the equilibrium γ phase.

2. Experimental

Ingots of a Cu-1.8wt%Be-0.2wt%Co alloy were prepared by melting 99.99wt%Cu, a Cu-3.8wt%Be and a Cu-10.5wt%Co master alloy. The alloy ingots were homogenized at 920 °C for 24 h in a vacuum. Specimen pieces were cut from the ingots and cold-rolled to a thickness of 3 mm. Then the specimens were solution-treated at 820 °C for 2 h in a vacuum, quenched into cold water, cold-rolled by 90% reduction and subsequently aged at 320 °C for various times in a salt bath.

Thin foils, 0.2 mm thick, for TEM observations were prepared by grinding the aged specimens with SiC papers and by electropolishing using a solution of 67% methanol and 33% nitric acid at -30 °C and 6.5 V in a twin-jet electropolisher. Microscopy was performed using a HITACHI H-9000NAR and a JEOL 2010FEF microscope operated at 300 and 200 kV, respectively. Electron micrographs were taken with the objective lens at or near to Scherzer defocus. Small variations in the defocus did not significantly affect the appearance of lattice fringes of precipitates. All HRTEM images were obtained with the beam parallel to a $<110>_\alpha$

direction in the Cu matrix. This is the optimum foil orientation for identifying each of the γ", γ'_I, γ_I, γ' and γ precipitated phases [6, 7]. Lattice fringe spacings in precipitates were measured on enlarged HRTEM images, using the Cu matrix $\{111\}_\alpha$ fringes as a standard.

Length changes ε_T on ageing were examined by measuring, with a micrometer, the distance between two scratched marks of 20 mm x 20 mm x 2 mm sized specimens. The length between the two marks is about 10 mm. 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 ageing at 320 °C for a time, respectively. The measurement accuracy of length change is in the order of 10^{-5} in strain.

X-ray analysis was carried out to examine the lattice constants of the solution-treated, cold-rolled and aged specimens. A diffractometer with a Cu target was used.

3. Results and discussion

3. 1 Length change, lattice parameter and precipitation behaviour

Figures 1a and b show the length change ε_T and the lattice parameter a, plotted as a function of ageing time t, for the specimen, cold-rolled by 90% reduction and subsequently aged at 320 °C for various times up to 350 h. The length change was measured along the direction of cold rolling. The data for the rolling-free specimen (RFS) [7] are also shown in Figures 1a and b. Length change of the rolled specimen (RS) increases from the initial stage of ageing, reaches a maximum value of (3.2±0.3) x 10^{-3} after ageing for about 24 h (8.64 x 10^4 s) and then decreases. When values of ε_T along several directions for the specimen aged for 3, 24 or 350 h were measured, the values for the specimen aged for each time were identical within experimental error. In other words, there existed no anisotropy in the length change. The fact that the RS expands by ageing is in agreement with the result obtained by Miki *et al*. [8] using a Cu-1.85wt%Be-0.24wt%Co alloy cold-rolled by 60% reduction. In contrast, length change of the RFS initially decreases, then remains constant for a while, increases slightly and again becomes constant. The initial contraction and the subsequent expansion are caused by precipitation of the γ' and the γ phase [7]. On the other hand, as seen in Figure 1b, the lattice parameter of the Cu matrix of the RS increases from the beginning of ageing and then saturates to a value of 0.3612 nm after ageing for about 24 h, which is very close to the lattice parameter of 0.3615 nm for Cu [9]. In contrast, the lattice parameter of the RFS shows initially no change for a while, then a rapid increase and, finally, the saturation value of 0.3612nm. This rapid increase is caused by precipitation of the γ' phase [7, 8].

In the Cu-1.8wt%Be-0.2wt%Co alloy polycrystals solutionized at 820ºC, large CoBe particles of about 1 μm with a B2 structure were rarely noticed. In the previous work [7], we estimated that 1.77wt%Be of 1.8wt%Be added was dissolved into the Cu matrix and the residual 0.03wt% Be was employed for constituting the CoBe particles. Therefore additional precipitation of the CoBe phase does not occur during ageing at 320°C and thus the length-change behaviour in Figure 1a is independent of the existence of CoBe particles.

The precipitated phases in the RFSs aged at 320 °C up to 350 h followed a GP zone → γ" → $γ'_I$ → $γ_I$ + γ' → γ sequence with ageing time [7]. In the lower portion of Figure 1a, the GP zone or each precipitated phase mainly observed at an ageing time is indicated. On the other hand, HRTEM observations of the RSs aged at 320 °C for various periods up to 350 h revealed complicated precipitation processes. Figure 2 presents the change in the volume fraction *f* of the GP zone and the γ", $γ'_I$, $γ_I$, $γ_m$ and γ' precipitated phase with ageing time *t*. The structure of the new-found $γ_m$ phase will be mentioned in 3. 2. *f* was determined by measuring the average volume and the number fraction of the GP zone and each phase at an ageing time, by using the lattice parameters of each phase in Table 1, and by applying the lattice parameter at the time in Figure 1b to the experimental data on the dependence of the lattice parameter on the Be concentration in the literature [10]. About one hundred precipitates at an ageing time were examined for this purpose. Each phase was identified mainly from analyses of HRTEM images taken along the [110] zone axis [6]. The GP zone and the γ", $γ'_I$ and $γ_I$ phase had a nearly disclike shape parallel to $\{001\}_α$ [6]. Then the average volume of the GP zone and each phase was obtained from measurements of the radius *r* and thickness *h*. The value of *h* of the GP zone was assumed to be identical to the diameter of Be atoms. In our previous work [6], the shape of the γ' precipitates was assumed to be a spheroid described in the *x*-*y*-*z* coordinates by $x^2/l^2+y^2/m^2+z^2/n^2 \leq 1$. Then we obtained $l : m : n = 7 : 28 : 59$ in the directions $[1\bar{1}3]_\alpha$, $[110]_\alpha$ and $[\bar{3}32]_\alpha$, respectively, when the incident beam direction was parallel to the $[110]_\alpha$ direction. Thus the average volume of the γ' precipitates can be evaluated by measuring the sizes of *l* and *n*.

Ageing the RS and RFS at 320 °C for 100 s produced the GP zones (Figures 1a and 2). In this stage of ageing, the lattice parameter of the RS increased slightly, whereas the RFS showed no essential change in the lattice parameter (Figure 1b). The number densities *N* of the GP zones in the RS and RFS aged for 100 s were, respectively, 1.3×10^{25} and 1.0×10^{24} m^{-3}, indicating that the introduction of dislocations by 90% cold rolling promotes formation of the GP zones. The values of *N* were obtained from $N=f/\pi r^2 h$. In the RS aged for 3 min, in addition to the GP zones, the γ" precipitated phase was observed, which consisted of primarily a two Be-layer structure separated by a matrix layer parallel to $\{100\}_\alpha$. An example is depicted in Figure 3. The RS aged for 10 min revealed the absence of the GP zones and the presence of the γ" and γ'_I precipitates, which were composed of two to five and five to eight Be-layers parallel to $\{100\}_\alpha$, respectively. The two to five Be-layers for γ" in the RS are generally large in comparison with the two Be-layers for γ" in the RFS [6, 7]. On ageing for 30 min, the γ" and γ'_I precipitates were also recognized in the RS, but there existed mainly γ'_I precipitates in the RFS. In this stage, the lattice parameter of the RS is considerably close to the saturation value of 0.3612 nm, while the RFS exhibits no essential change in the lattice parameter even after 30 min. The lattice parameter of the RFS attained nearly the saturation value when aged for 3 h (1.08×10^4 s). Ageing the RS for 3 h produced γ_I precipitates consisting of about ten Be-layers, in addition to the γ" and γ'_I precipitates, and the heterogeneous precipitation of γ' phase on γ_I was rarely noticed. In contrast, the RFS aged for

3 h showed primarily the existence of the γ' precipitates (Figure 1a). The γ_I and γ' phases in the RFS aged for 3 h in Figure 4a are composed of six Be-layers parallel to $(001)_\alpha$ and about forty Be-layers nearly parallel to $(001)_\alpha$. The retardation of the transformation from the GP zones to γ' via γ'', γ'_I and γ_I is evident for the RS. During ageing of the RFS between about 30min and 3h, the γ' phase forms heterogeneously on the γ_I phase under a high degree of Be supersaturation and grows rapidly, resulting in a low supersaturation. In contrast, the supersaturation of the Cu matrix of the RS is already considerably low after ageing for 30 min and thus the heterogeneous formation and growth of γ' are suppressed. The γ_m phase was noticed on ageing for 12 h (4.32×10^4 s). After ageing for 24 h at which the length change reaches the maximum value, the γ'_I, γ_I, γ_m and γ' phases coexist (Figure 2). While the length change of the RS decreases during ageing from 24 (8.64×10^4 s) to 350 h (1.26×10^6 s), the volume fraction of γ' increases, those of γ'_I and γ_m decrease and that of γ_I remains unchanged. At 350 h the γ'_I phase was no longer observed. As a consequence of the suppression of the heterogeneous formation of γ' on γ_I precipitates in the RS, the size and Be-layer number of the γ_I precipitates are much larger than those of the γ_I precipitates in the RFS (Figure 4b).

An inset in Figure 3 is the simulated image of the γ'' phase obtained with specimen thickness=20 nm and Scherzer defocus Δf=40 nm, based on the structure of the γ'' phase in Table 1. The simulations were carried out by the multi-slice method. The microscope parameters used were as follows: high voltage HV=300 kV, spherical aberration Cs=0.7 mm, spread of the focus=5 nm and slice thickness=0.3 nm.

3.2 Structure and misfit strains of γ_m phase

Figure 5a depicts a HRTEM image of a γ_m precipitate in the specimen, cold-rolled by 90% reduction and then aged at 320 ºC for 220 h (7.92×10^5 s). The zone axis is parallel to the $[110]_\alpha$ direction. Figure 5b is a HRTEM image of a γ_m precipitate in another grain in the same specimen. In this case, the zone axis is parallel to $[1\bar{1}0]_\alpha$. The γ_m precipitates in Figures 5a and b have a structure of alternate Be and Cu layers parallel to $(001)_\alpha$ and consist of about thirty Be-layers. In the γ_m precipitates, lattice fringes nearly parallel to $(1\bar{1}0)_\alpha$ and those parallel to $(110)_\alpha$ also are visible. The average spacings of the lattice fringes, corresponding to the $(100)_m$ (//$(110)_\alpha$), $(010)_m$ (·//·$(1\bar{1}0)_\alpha$) and $(001)_m$ (//$(001)_\alpha$) planes of the γ_m precipitates, were measured as a=b=0.263±0.003 nm and c=0.279±0.004 nm, respectively. About fifty precipitates viewed along the $[110]_\alpha$ and $[1\bar{1}0]_\alpha$ zone axes were investigated. The angles α and β between the $[010]_m$ and $[001]_m$ and between $[100]_m$ and $[001]_m$ were α =82.7±0.5° and β=89.8±0.4° on average. The angle γ between $[100]_m$ and $[010]_m$ was obtained as γ =90.3±0.5° from an analysis of extra reflections in the $[001]_\alpha$ SADP as in our previous study [6]. Therefore the γ_m phase is body-centred monoclinic with the lattice parameter values in Table 1. As revealed in Figures 5a and b, the Bain orientation relationship is satisfied between the γ_m phase and the surrounding Cu matrix: $[110]_\alpha$//$[100]_m$; $(001)_\alpha$//$(001)_m$.

The precipitate sequence for the rolling-free Cu-Be-Co alloy aged at 320 °C is: GP zone → γ” → γ'_I → γ_I + γ’ → γ [7]. The γ”, γ'_I, γ_I, γ’ and γ phases do not independently nucleate but are closely related to the preceding phase [6]. Similarly, it can be stated that since the γ_m phase forms under a low degree of supersaturation between 3 and 12 h, it does not independently nucleate, but consecutively transforms from the γ'_I or γ_I phase existing between 3 and 12 h (Figure 2). The volume fraction of γ_I remains nearly unchanged up to 350 h, while that of γ_m decreases and become almost zero at 350 h (Figure 2). Therefore it can be concluded that the γ_m phase does not transform from the γ_I phase but continuously transforms from the γ'_I phase.

Next, we will estimate the misfit strains of the γ_m phase. From the lattice parameter values of the γ_m phase (Table 1) and Cu matrix (=0.3612 nm) and the Bain orientation relationship between the γ_m phase and Cu matrix, the lattice misfits ε_{11}, ε_{22}, and ε_{33} along $[100]_\alpha$, $[010]_\alpha$ and $[001]_\alpha$ are calculated as 0.03, 0.03 and –0.23. The absolute value of ε_{33} is very large and thus the misfit strain ε_{33} should be released. Figure 5c is an enlarged image of the outlined frame in Figure 5a after noise filtering by fast Fourier transformation and inverse fast Fourier transformation. Misfit dislocations with a Burgers vector $\boldsymbol{b}$=[001]$_m$ observed at the interface between the γ_m precipitate and the Cu matrix are spaced approximately four (001)$_m$ spacings of γ_m apart, namely on average, four (001)$_m$ spacings on the γ_m phase side of the interface are matched with three (001)$_\alpha$ spacings on the Cu side of the interface. This causes the averaged misfit strain ε_R in [001]$_\alpha$ given by $\varepsilon_R = (4d_m - 3d_\alpha) / [(4d_m + 3d_\alpha) / 2] \approx 0.03$. Here d_m and d_α are the (001)$_m$ spacing of γ_m phase and the (001)$_\alpha$ spacing of Cu matrix. The estimated misfit strains are shown in Table 2. Table 2 also lists the misfit strains of the γ_I phase, together with those of the GP zone and γ'', γ'_I, γ' and γ phases obtained by length-change measurements [5, 7]. The misfit strains of γ_I were determined from the lattice parameter values of γ_I in Table 1 and Cu, and the Bain orientation relationship between the γ_I phase and Cu matrix [6, 7]. The absolute values of ε_{33} for γ_I and γ_m are small compared with those for the other phases.

3.3 Comparison with calculated length-changes

In our previous study [7], we have shown that the length-change behaviour of the rolling-free Cu-1.8wt%Be-0.2wt%Co alloy polycrystals during ageing at 320 and 500 °C is well represented by the equation:

$$\varepsilon_T = \frac{f(\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33})}{3} + (1 - f)\varepsilon_a, \tag{1}$$

where ε_a is the dimensional change due to the loss of Be solute atoms from the solid solution and given by

$$\varepsilon_a = \frac{a - a_0}{a_0}, \tag{2}$$

where a_0 is the lattice parameter of the solution-treated specimen. Equation (1) indicates that there is no anisotropy in the length change. In fact, the length change of the rolled specimen showed no anisotropy, as mentioned in 3. 1. The measured values of ε_T for the rolling-free specimen were in good agreement with the ε_T values calculated using Equations (1) and (2), as seen in Figure 1a.

Using the values of ε_{11}, ε_{22} and ε_{33} for each phase in Table 2, the values of f for each phase in Figure 2, and the values of ε_a estimated by the lattice parameter values in Figure 1b, we had the values of ε_T, shown by closed triangles in Figure 1a. The measured values of ε_T at ageing times are almost identical to the calculated values of ε_T at the times. The maximum value of $(1-f)\varepsilon_a$ estimated from Equation (2) is 8.0 x 10^{-3}, which is larger than the measured maximum value of $\varepsilon_T = 3.2\times10^{-3}$ at 24 h in Figure 1a. The difference between the maximum values of $(1-f)\varepsilon_a$ and ε_T is brought about by the existence of γ'_I, γ_I, γ_m and γ' at 24 h in Figure 2. If there is assumed to exist only the γ' phase after ageing for 24 h, the value of ε_T is calculated as -1.8 x 10^{-3} from Equations (1) and (2), owing to the large negative value of ε_{33} for the γ' phase in Table 2. This value is nearly identical to the measured value of the RFS on ageing for 24 h in Figure 1a. Therefore we conclude that the maximum expansion of the RS are attributed to both the expansion based on the decrease of Be solute atoms in the matrix and the contraction due to the existence of the γ'_I, γ_I, γ_m and γ' phases, and the successive contraction is caused by the increase in f of the γ' phase, which has the large negative misfits in Table 2.

4. Conclusions

1. Ageing a solution-treated and then 90 % cold-worked Cu-1.8wt%Be-0.2wt%Co alloy at 320ºC up to 350 h produced a gradual expansion to a maximum and subsequent contraction of the alloy. Both the expansion based on loss of the Be solute atoms and the contraction based on precipitation of the γ'_I, γ_I, γ_m and γ' phases were responsible for the maximum expansion. The decrease in amounts of the γ'_I and γ_m phases and the increase in amount of the γ' phase caused the subsequent contraction.

2. The new-found γ_m phase was composed of alternate Be and Cu matrix layers parallel to $\{001\}_\alpha$ of the matrix, had a body-centred monoclinic lattice with a=b=0.263 nm and c=0.279 nm and α=83° and exhibited the Bain orientation relationship to the matrix.

3. The γ_m and the γ_I phase transformed continuously from the GP zone via γ" and γ'_I. The 90% cold-rolling promoted the formation of GP zones but suppressed the transformation from the GP zone to γ' via γ", γ'_I and γ_I.

Acknowledgements

We thank Mr K. Higashimine of the Centre for Nano Materials and Technology, Japan Advanced Institute of Science and Technology, for the TEM observation by HITACHI H9000-NAR. A part of this work was conducted in the Kyoto-Advanced Nanotechnology Network, supported by the “Nanotechnology Network” of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. This work was partially supported by a Grant-in-Aid for Science Research from The Ministry of Education, Culture, Sports and Technology under Grant No.19560742.

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Tables with captions

Table 1 Lattice parameters and system of γ”, γ'_I, γ_I, γ’and γ precipitated phases in Cu-Be single-crystal specimens, obtained by Monzen *et al*. [6] from analyses of HRTEM images and selected-area diffraction patterns. Also shown are those of new-found γ_m phase in the present study.

Phase	Lattice parameter	Lattice system
γ''	$a = b = 0.254$ nm, $c = 0.292$ nm	Body-centered tetragonal
γ'_I	$a = b = 0.254$ nm, $c = 0.324$ nm, $\alpha = 87°$	Body-centered monoclinic
γ_I	$a = b = 0.254$ nm, $c = 0.352$ nm	Body-centered tetragonal
γ_m	$a = b = 0.263$ nm, $c = 0.279$ nm, $\alpha = 83°$	Body-centered monoclinic
γ'	$a = 0.254$ nm, $b = c = 0.268$ nm	Body-centered tetragonal
γ	$a = 0.268$ nm or 0.280 nm	Body-centered cubic

Table 2 Misfit strains of GP zones and γ", γ'$_I$, γ'and γ phases, previously estimated using length-change measurement results [5, 7] and of γ_I and γ_m phases, calculated using the lattice parameters of γ_I and γ_m in Table 1 and Cu matrix. See text for the value of ε_{33} of γ_m.

	GP zone	γ"	γ'$_I$	γ_I	γ_m	γ'	γ
ε_{11} ($=\varepsilon_{22}$)	−0.01	−0.01	−0.01	−0.01	0.03	−0.03	−0.03
ε_{33}	−0.10	−0.11	−0.11	−0.03	0.02	−0.09	−0.08

Figure captions

Fig. 1 Ageing time dependences of (a) the measured length-change ε_T and (b) lattice parameter of Cu matrix *a* for Cu-1.8wt%Be-0.2wt%Co specimens aged at 320ºC after cold-rolled by 90% reduction. Also shown are data for the specimens without cold rolling [7]. Representative error bars are shown. The calculated values of ε_T are indicated by closed triangles and circles in (a).

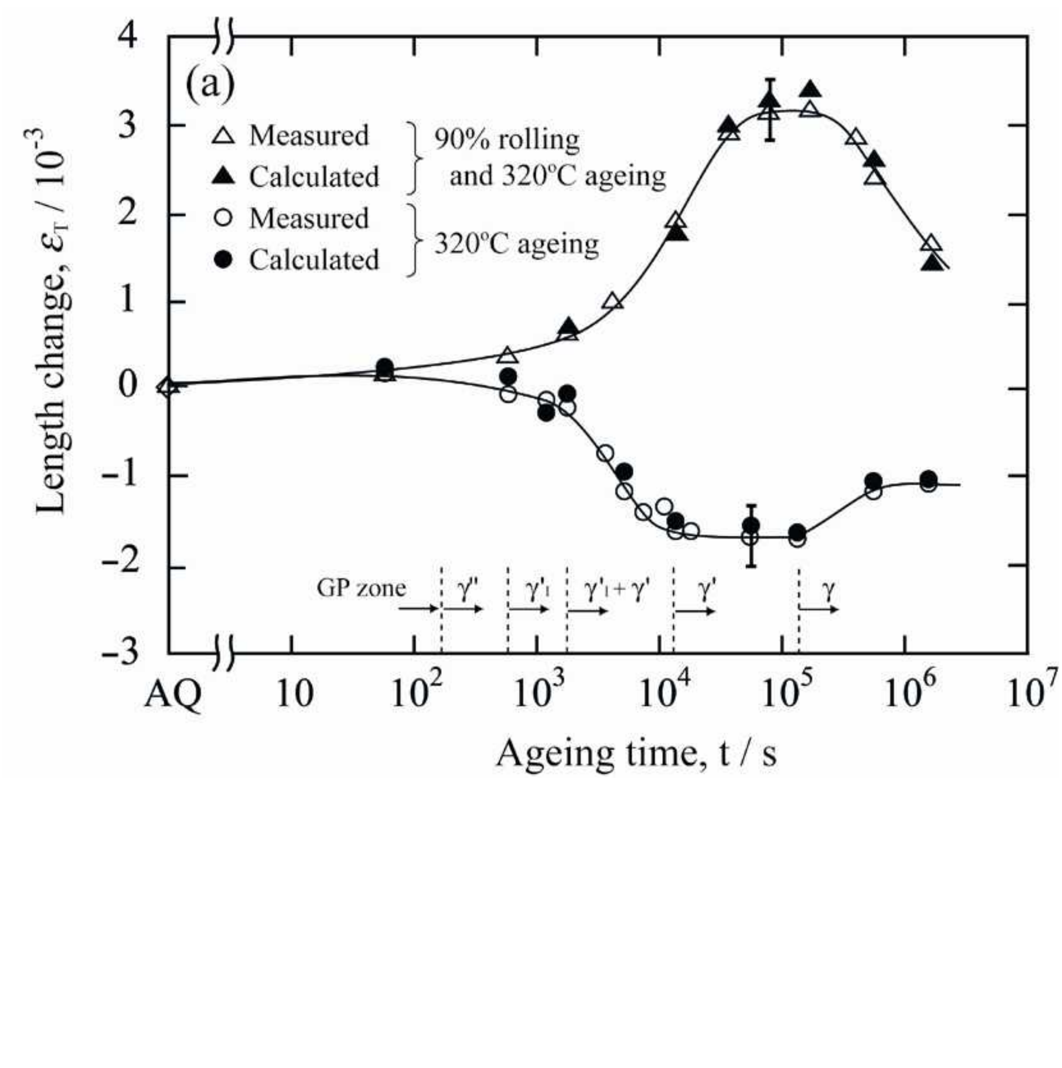
Fig. 2 Ageing time dependence of the volume fraction *f* of GP zones and γ'', γ'_I, γ_I, γ_m and γ' precipitated phases in Cu-Be-Co specimens aged at 320ºC after cold-rolled by 90% reduction.

Fig. 3 HRTEM image of a γ'' precipitate in a Cu-Be-Co specimen aged at 320 ºC for 3 min after cold rolling by 90% reduction.

Fig. 4 HRTEM images of (a) a precipitate consisting of γ_I and γ' phases in a Cu-Be-Co specimen aged at 320ºC for 3h without cold rolling and (b) a large γ_I precipitate in a Cu-Be-Co specimen aged at 320ºC for 300 h after cold rolling by 90% reduction.

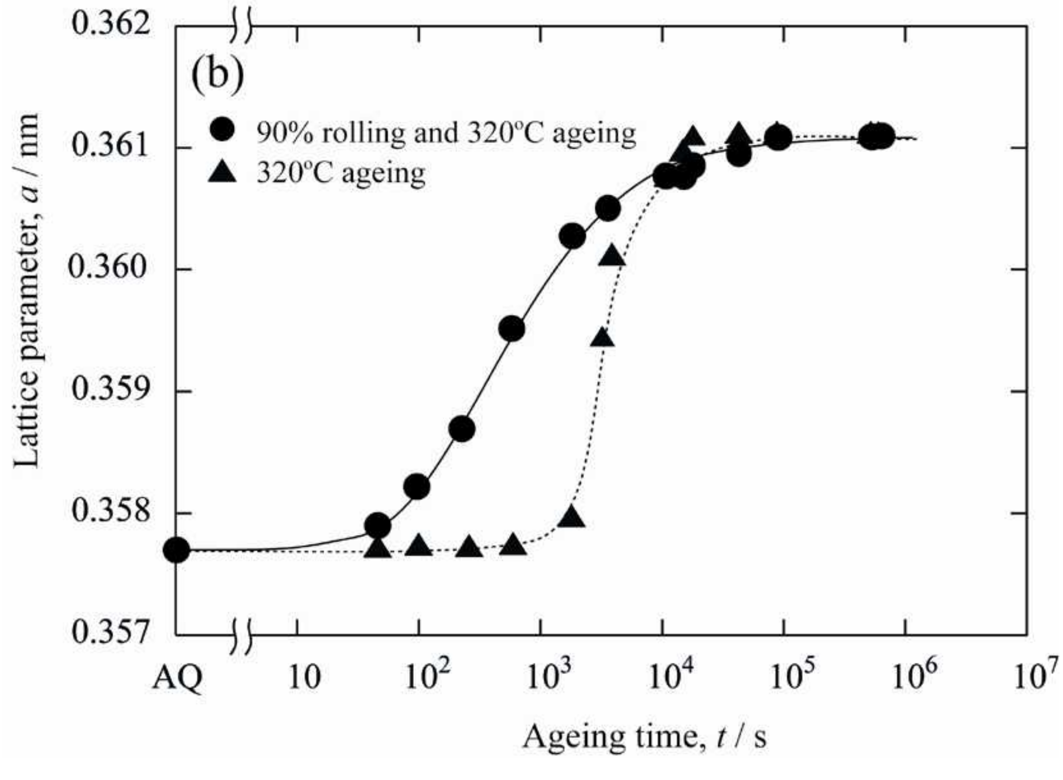
Fig. 5 (a), (b) HRTEM images of γ_m precipitates in Cu-Be-Co specimens aged at 320 ºC for 220 h after cold rolling by 90% reduction, taken along (a) the $[110]_\alpha$ and (b) $[1\bar{1}0]_\alpha$ zone axes. (c) Enlarged HRTEM image of the outlined frame in (a) after noise filtering by means of fast Fourier transformation and inverse fast Fourier transformation.

Fig. 1(a)



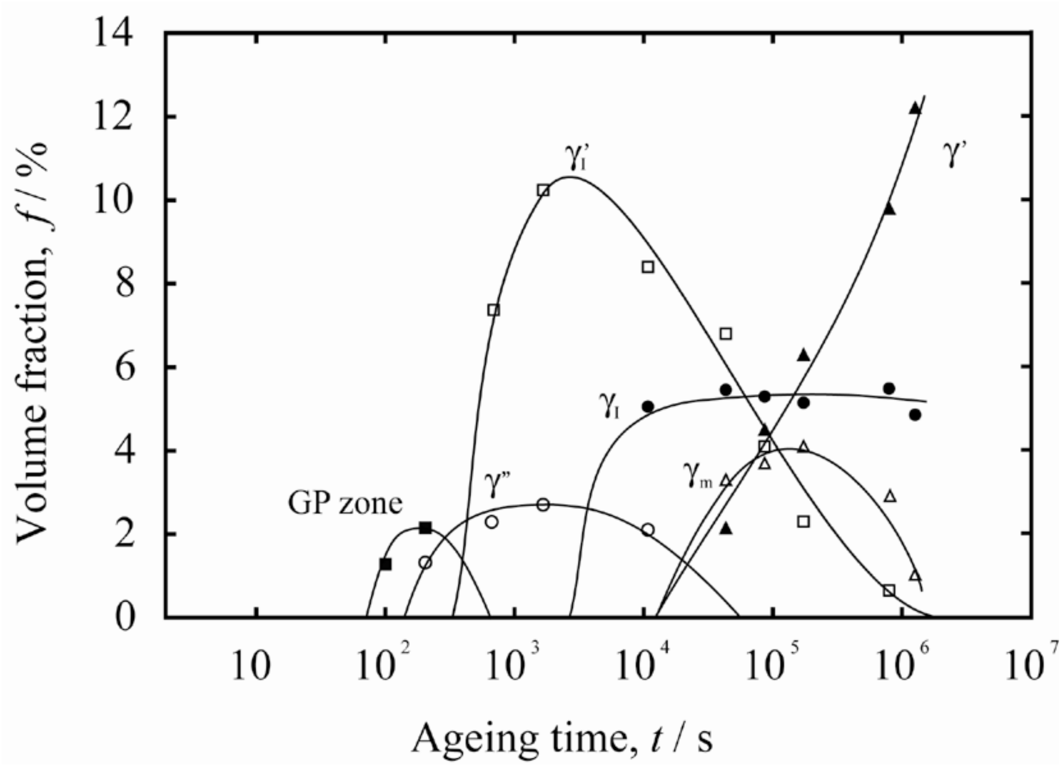
(a)
Measured
Calculated
90% rolling and 320ºC ageing
Measured
Calculated
320ºC ageing
Length change, ε_T / 10^{-3}
Ageing time, t / s
GP zone
γ''
γ'I
γ'I + γ'
γ'
γ
AQ
10
10^2
10^3
10^4
10^5
10^6
10^7
4
3
2
1
0
-1
-2
-3

Fig. 1(b)



(b)
90% rolling and 320°C ageing
320°C ageing
Lattice parameter, a / nm
0.362
0.361
0.360
0.359
0.358
0.357
AQ
10
10²
10³
10⁴
10⁵
10⁶
10⁷
Ageing time, t / s

Fig. 2



14
12
10
8
6
4
2
0
Volume fraction, f / %
10
10²
10³
10⁴
10⁵
10⁶
10⁷
Ageing time, t / s
γI'
γ'
γI
γm
γ"
GP zone

Fig. 3

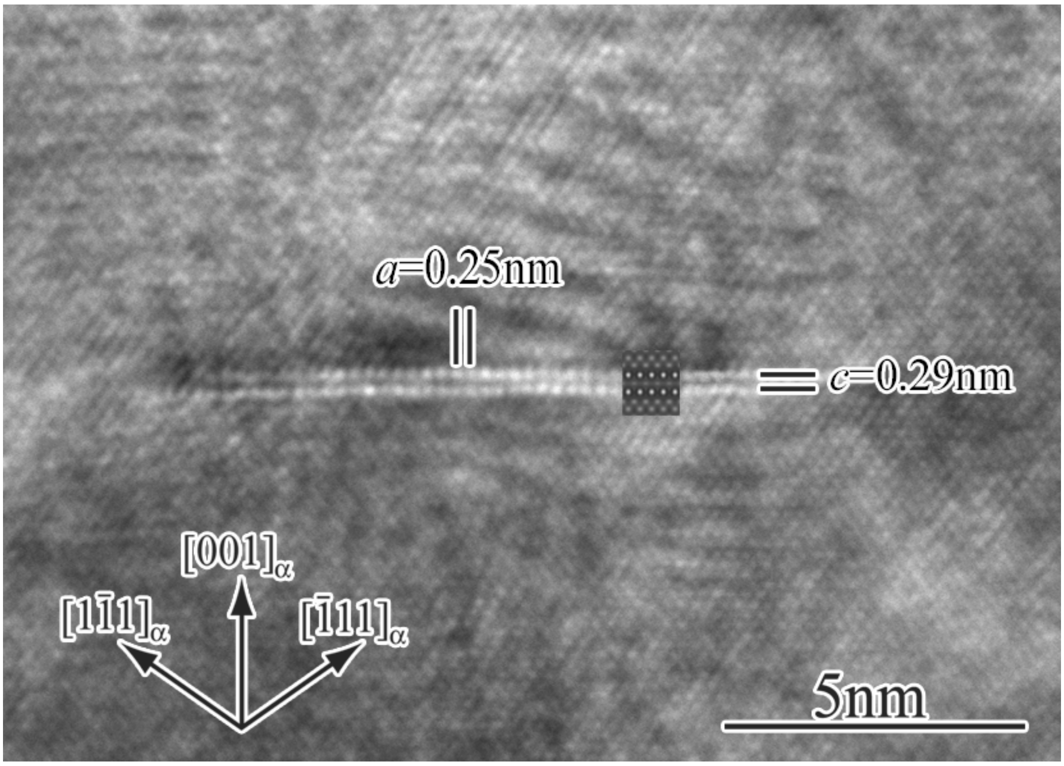
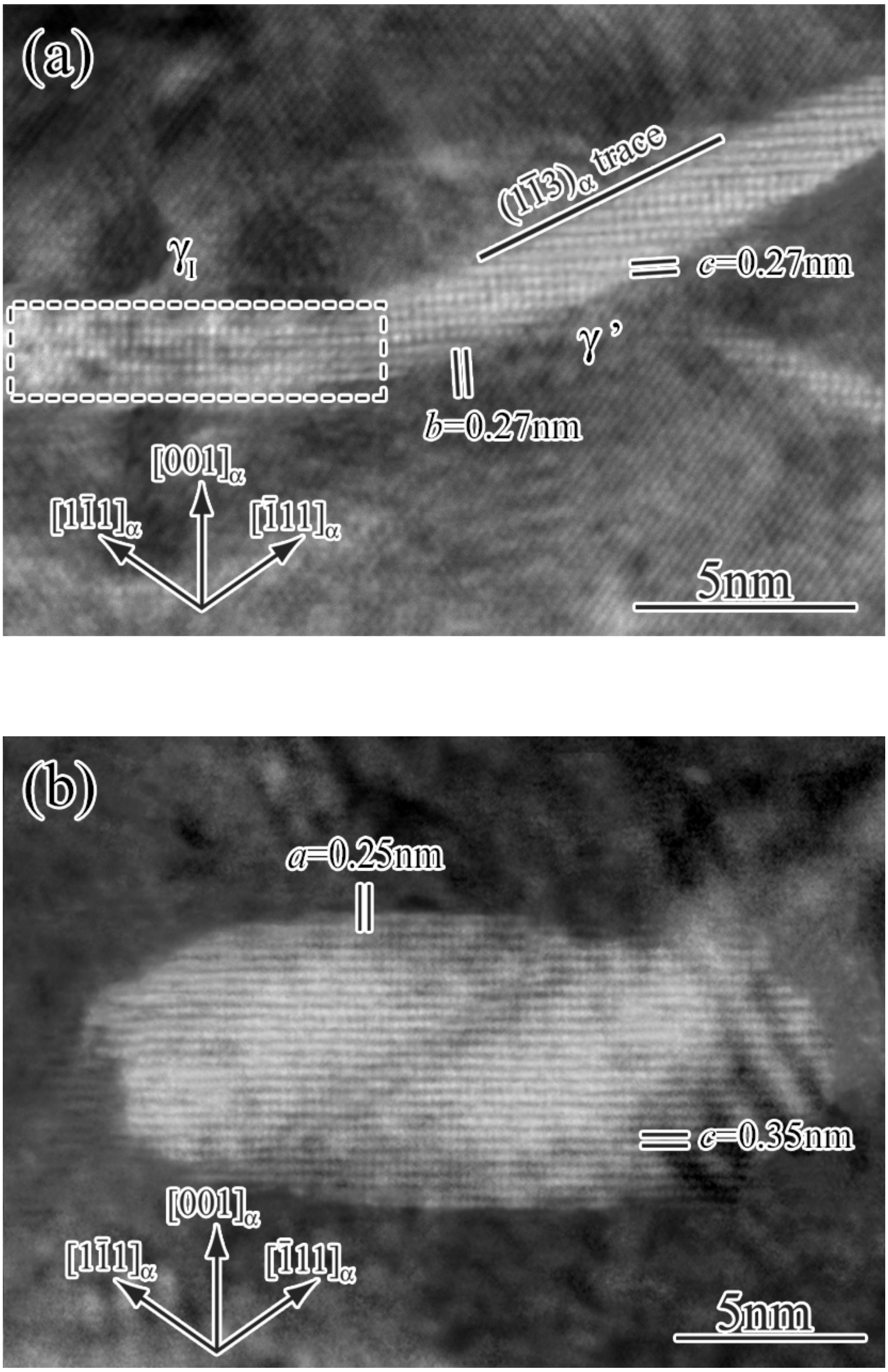
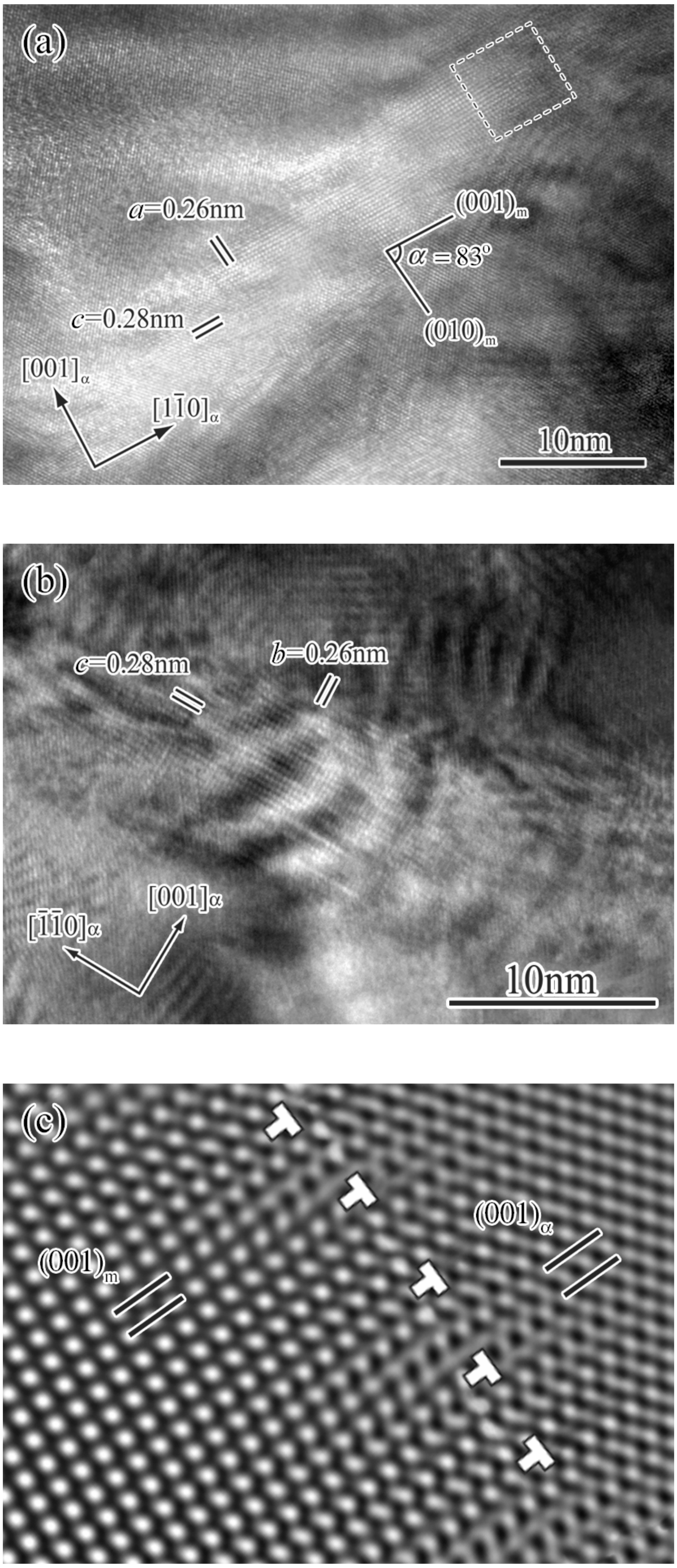


Fig. 4



(a)
γ_I
$(1\bar{1}3)_\alpha$ trace
c=0.27nm
γ'
b=0.27nm
$[001]_\alpha$
$[1\bar{1}1]_\alpha$
$[\bar{1}11]_\alpha$
5nm
(b)
a=0.25nm
c=0.35nm
$[001]_\alpha$
$[1\bar{1}1]_\alpha$
$[\bar{1}11]_\alpha$
5nm

Fig. 5



(a)
a=0.26nm
c=0.28nm
$(001)_m$
$\alpha = 83^o$
$(010)_m$
$[001]_\alpha$
$[1\bar{1}0]_\alpha$
10nm
(b)
c=0.28nm
b=0.26nm
$[001]_\alpha$
$[\bar{1}\bar{1}0]_\alpha$
10nm
(c)
$(001)_\alpha$
$(001)_m$