A Basic Study of Dynamic Recrystallization in Cu-Sn-P Alloy for High Strength Copper

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Dynamic recrystallization (DRX) behavior in a newly developed Cu-Sn-P alloy was systematically investigated. Hot compression tests were performed on alloy samples having different crystalline conditions, i.e., as-cast coarse-grained polycrystalline and orientation-controlled bicrystals. Also tested were Cu-Sn-P alloys with varying Sn content. As a result of Sn addition, the Cu-Sn-P alloy was found to undergo DRX that is much delayed compared with that of a conventional Cu-P alloy. The delayed DRX is considered to have increased the flow stress and strain required for processing the Cu-Sn-P alloy. When compressed under conditions that are close to the conditions of the actual operation, the alloy was found to exhibit a significantly inhomogeneous microstructure. This structure seemed to be refined and homogenized as a result of static recrystallization during the subsequent cooling period after extrusion. It is concluded that the DRX in Cu-Sn-P alloy is dominated by discontinuous type DRX governed by the annealing twins formed behind the migrating grain boundaries.

Introduction

Phosphorous-deoxidized copper (JIS H3300 C1220) is widely used all over the world for room air conditioners, the heat exchangers of heat-pump water heaters and as a piping material. Lately, the application of a high pressure refrigerant, such as CO_2, and the increased need for cost reduction as a result of the rising price of copper have led to the development and production of high strength copper tubes[1), 2)].

The high-strength copper alloys are materials newly being used for copper tubes and contain elements such as Co and Sn. As a result, they are empirically known to be vastly different in terms of extrudability and the like from phosphorous-deoxidized copper, the pure-type copper in conventional use.

There are 3 types of high strength copper tubes. Among them, the solid solution strengthening type Cu-Sn-P (KHRT®[3)]) is the most difficult material to extrude. This material was selected for the present study and the following 3 types of samples were prepared:

(1) materials with coarse columnar grain structures machined from hot extrusion billets;
(2) bicrystals simulating the above coarse columnar grain structures; and
(3) materials with fine grains containing various amount of Sn.

These 3 types of samples were subjected to hot compression tests to study the details of their dynamic recrystallization behaviors. As a result, systematic and basic knowledge has been obtained on their deformation behavior during hot extrusion, crystal grain refinement by microstructure control, and so on, as reported below.

1. Dynamic recrystallization

We first describe dynamic recrystallization, a consistent theme of the present paper. When a material is deformed in a high temperature region, the dislocation density increases to initiate work hardening, increasing the flow stress. Dynamic recrystallization is a type of recrystallization that is driven by the strain energy and the decrease in dislocation density that occur during the deformation. Hence the dynamic recrystallization results in the formation of new grains containing neither dislocation nor strain, which results in a distinctive phenomenon of work softening.

Fig. 1 shows an example of the typical stress-strain curves associated with dynamic recrystallization during deformation at high temperatures. After an elastic deformation, the flow stress is increased by work hardening caused by the increase in dislocation density and strain energy that takes place during plastic deformation. Then the work hardening

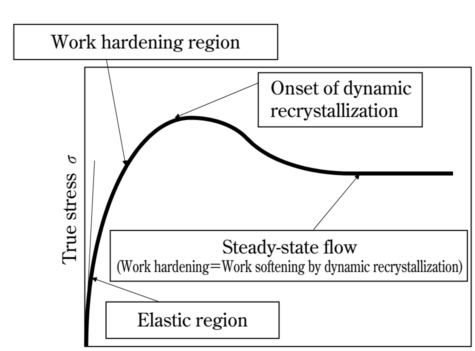

Fig. 1 Typical flow curve in dynamic recrystallization

reaches a peak stress, and an extensive dynamic recrystallization occurs to release the strain energy. This eventually leads to work softening, decreasing the flow stress. Under a yet higher strain, the work hardening balances with the work softening, resulting in a steady state deformation in which the flow stress becomes constant[4)-7)].

Analyzing the tress-strain curves obtained during hot compression and observing the resulting microstructure provide the basic knowledge of, for example, the deformation behavior and grain refinement necessary for tube production and microstructural control.

2. The dynamic recrystallization behavior of the material with coarse grains

2.1 The coarse grain material consisting of columnar crystals

The dynamic recrystallization behavior of a cast material consisting of coarse columnar crystals was studied in order to clarify the change in structure of high-strength copper KHRT during hot extrusion at an actual production site. The process for producing a copper tube includes hot-extruding a cast-billet to produce a mother tube. The cast material comprises chill crystals in the circumference, free crystals in the center and coarse columnar crystals in the major portion of the tube[8), 9)].

Dynamic recrystallization is less likely to occur when the crystal grain is coarser[10)]. This is due to the fact that coarser grains provide a smaller number of grain boundaries that serve as the preferential nucleation sites for recrystallization[11)]. Therefore, the coarse grains (columnar crystals) govern the dynamic recrystallization behavior of the cast structure.

2.2 Experimental method

Two types of samples were used: a phosphorous-deoxidized copper tube, having a composition of Cu-0.025mass% P (hereinafter referred to as "Cu-P"), which has been conventionally and widely used for heat exchanger applications; and a high strength copper tube, KHRT, having a composition of Cu-0.65 mass%Sn-0.025mass%P (hereinafter referred to as "Cu-0.65Sn-P"), which has been newly developed and used commercially. A square rod sample, having a dimension of $6\times 9\times 13mm^3$, was machined from the columnar crystal portion of each billet and was subjected to compression testing. The initial grain sizes, determined by a cutting method in accordance with JIS H0501, were 5.8mm for Cu-P and 5.3mm for Cu-0.65Sn-P. A vacuum high-temperature compression testing machine (Instron type) was used for the compression tests at temperatures of $T=1{,}023$ to 1,253K and a strain rate of $\dot{\varepsilon}=2.0\times 10^{-4}$ to $2.0\times 10^{-1}s^{-1}$. Each test was performed until the true strain reached $\varepsilon=0.8$. As schematically shown in **Fig. 2**, the direction of the compression axis of the columnar crystal sample was set so as to be parallel to the casting direction. Each sample was water-cooled within 1s after the compression test such that the structure formed during the high-temperature working was quenched.

2.3 Experimental results and discussion

Fig. 3 shows the true stress-true strain curves of the Cu-P cast materials compressed at strain rates of $\dot{\varepsilon}=2.0\times 10^{-4}$ to $2.0\times 10^{-1}s^{-1}$ at a temperature of $T=1{,}073$K. The stress-strain curves obtained have a shape resembling the one in Fig. 1, shown as a typical example of dynamic recrystallization. The phenomenon occurring during this time is as explained in Section 1.

Fig. 4 shows the true stress-true strain curves of the Cu-0.65Sn-P cast materials compressed at a temperature of $T=1{,}153$K and at strain rates of $\dot{\varepsilon}=2.0\times 10^{-4}-2.0\times 10^{-1}s^{-1}$. The stress-strain curves have a shape that is different from the one for Cu-P. Firstly, these curves exhibit clear yielding in the initial deformation region, in the vicinity of true strain from 0.02 to 0.06, and subsequently exhibit

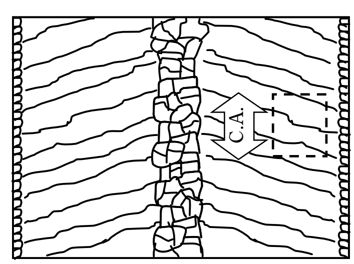

Fig. 2 Schematic illustration of billet in section
Rectangular area of dotted line : columnar structure, C.A. : compression axis

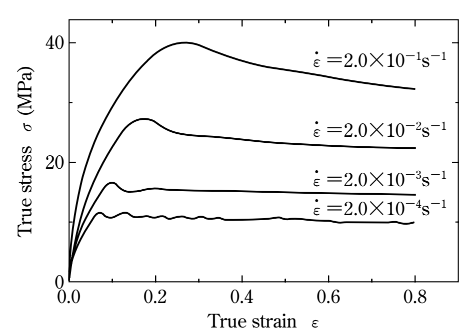

Fig. 3 Flow curves of Cu-P alloy billet samples compressed at 1,073K at various true strain rates

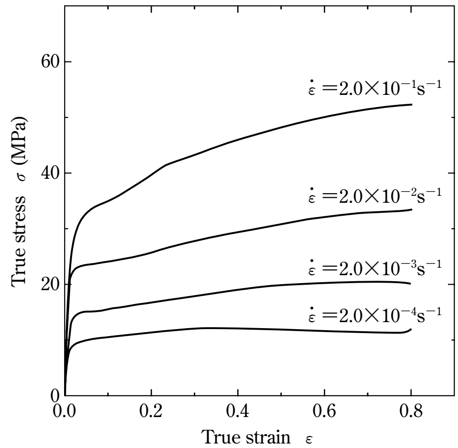

Fig. 4 Flow curves of Cu-0.65Sn-P alloy billet samples compressed at 1,153K at various true strain rates

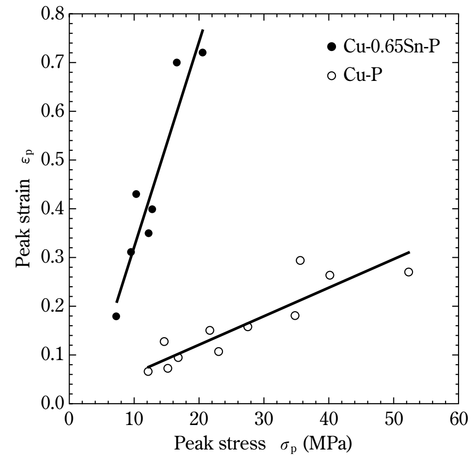

Fig. 5 Relationship between peak stress and peak strain of Cu-0.65Sn-P and Cu-P alloy billet samples

large and significant work hardening. This is considered to be caused by the solid-solution strengthening effect of Sn. Further increase in the strain makes the increase in flow stress moderate, which is considered to be attributable to dynamic recovery/recrystallization. In particular, when the strain rate is as large as $\dot{\varepsilon}=2.0\times10^{-1}s^{-1}$ and $\dot{\varepsilon}=2.0\times10^{-2}s^{-1}$, the results show neither the clear peak stress nor the work softening exhibited by the Cu-P.

Each of the Cu-P and Cu-0.65Sn-P samples was tested at three different temperatures and four different strain rates. **Fig. 5** shows the relationship between the peak stress and peak strain, both obtained from all the true stress-true strain curves. It should be noted that the Cu-0.65Sn-P materials, not showing any peak stress until $\varepsilon=0.8$, are regarded as having no data for peak stress and peak strain. Furthermore, for the stress-strain curves of Cu-P, in which the curves show more than one peak stress, the value for the stress and strain of the first peak are taken as data.

For both the alloys, the peak stress and peak strain are found to be in a linear relationship regardless of the temperature and strain rate. However, there is a significant difference between the Cu-P and Cu-0.65Sn-P in the slope of the linearity. The slope for the Cu-0.65Sn-P is greater than that for the Cu-P, indicating that the amount of strain that initiates/induces dynamic recrystallization for Cu-0.65Sn-P is greater than that for Cu-P. This is because the addition of Sn significantly delays the initiation of dynamic recrystallization. This agrees with the rule of thumb, empirically obtained at the manufacturing site, that the mother tube of the high-strength copper, KHRT, Cu-0.65Sn-P, is more difficult to extrude than the conventional phosphorous deoxidized copper, Cu-P.

The Cu-0.65Sn-P was subjected to a compression test at a high temperature of $T=1{,}153$K and $\dot{\varepsilon}=2.0\times10^{-1}s^{-1}$ up to a strain of $\varepsilon=0.8$. The test samples were annealed for either 10s or 30s. The resulting microstructures, as well as the as-quenched structure, are shown in **Fig. 6**. The structure immediately after the hot-working was quite inhomogeneous, showing many deformation zones formed inside the coarse un-recrystallized grains, as well as the development of necklace-like fine grains formed on the old grain boundaries. This structure, however, changed into a finer and almost homogeneous recrystallization structure as the subsequent annealing time was increased. This is considered to be a result of the high dislocation density and strain energy accumulated in the grains and on the grain boundaries serving as a driving force for static recrystallization and making the structure homogeneous. Considering actual extrusion, only certain regions are considered to have

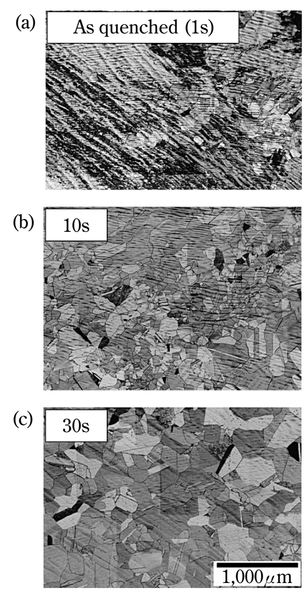

Fig. 6 Microstructure of Cu-0.65Sn-P alloy billet samples deformed to ε =0.8 at 1,153K at strain rate of $\dot{\varepsilon}$=2.0 ×$10^{-1}s^{-1}$(a), followed by annealing at 1,153K for 10s(b) and 30s(c)

a dynamically recrystallized structure immediately after the extrusion, but the structure is annealed during the subsequent cooling and changes into a perfectly recrystallized structure. These experimental facts provide extremely useful information for microstructure control, or the structural homogenization and refinement, of the actually extruded materials. The fact that the structure contains many annealing twins indicates the occurrence of discontinuous static recrystallization.

3. The dynamic recrystallization behavior of bicrystals

3.1 The bicrystal as a material, simulating cast material

Bicrystals were prepared as simple model materials simulating the cast materials with coarse columnar crystals described in Section 2. The bicrystals were used to study the basics of, for example, the dynamic recrystallization behavior in the vicinity of a grain boundary that is important as the formation site of dynamic new grains.

Grain boundaries and precipitates can serve as preferential formation sites for new grains geometrically and crystallographically. Dynamically recrystallized grains are reported to be formed preferentially on grain boundaries by a bulging mechanism[11), 12)]. The deformation behaviors of, and structural changes in, the grain boundaries and their vicinities, locations playing a very important role in dynamic recrystallization, were systematically studied using the orientation controlled twin crystals prepared to simulate the coarse grain columnar crystals.

3.2 The experimental method

The Cu-0.65Sn-P (high-strength copper tube, KHRT) was used as the base material for the Bridgman method (a method involving a seed crystal prepared by a pull-up method, on which material is sequentially solidified to produce a single crystal having a crystallographic orientation that is the same as that of the seed crystal) to prepare a bicrystal having a [011] twist grain boundary with a grain boundary misorientation of 18 degrees (hereinafter referred to as an "18° bicrystal"). Square rod specimens, each having a dimension of 6×9×12mm, were machined from the bicrystal by an NC electric discharge machine, such that their grain boundaries became vertical to the compression axis (so as to simulate the columnar crystal being extruded). The specimens were subjected to the high temperature compression test. The test temperature was set to be $T=1{,}073$K and the strain rate to $\dot{\varepsilon}=2.0\times10^{-3}$ to $2.0\times10^{-1}\mathrm{s}^{-1}$, and the tests were conducted until the true strain reached $\varepsilon=0.2$, 0.5 and 1.0. The specimens were water-cooled within 1s after the compression test so as to quench the structure formed during the high temperature working. Furthermore, the crystal orientations of the deformation microstructures in the vicinity of grain boundaries on the longitudinal section, parallel to the compression axis, were analyzed using a crystal orientation analysis apparatus (Orientation Imaging Microscopy, hereafter "OIM").

3.3 Experimental results and discussion

Fig. 7 shows the stress-strain curves of the 18° bicrystal samples compression tested at a high temperature. It is confirmed that the curve for the lowest strain rate, $\dot{\varepsilon}=2.0\times10^{-3}\mathrm{s}^{-1}$, exhibits a peak stress at around $\varepsilon=0.5-0.6$ and subsequent work softening before exhibiting a steady state deformation. On the other hand, the curve for $\dot{\varepsilon}=2.0\times10^{-2}\mathrm{s}^{-1}$ appears to reach the peak stress at a higher strain around $\varepsilon=0.8$. The curve for $\dot{\varepsilon}=2.0\times10^{-1}\mathrm{s}^{-1}$ at one point shows a steady state deformation, but subsequently exhibits work hardening. As the strain rate increases, the stress value becomes higher, implying that dynamic recrystallization is less likely to occur. Comparing Fig. 4 and Fig. 7, despite the 80K difference in testing temperature, the bicrystal exhibit greater stress value for a given strain rate, implying that dynamic recrystallization does not occur on a large scale. This is caused by the relation between crystal grains and dynamic recrystallization from the aspect of the occurrence point, as will be discussed in Section 4.3.

The 18° bicrystals of Cu-0.65Sn-0.025P were compressed at a high temperature under the

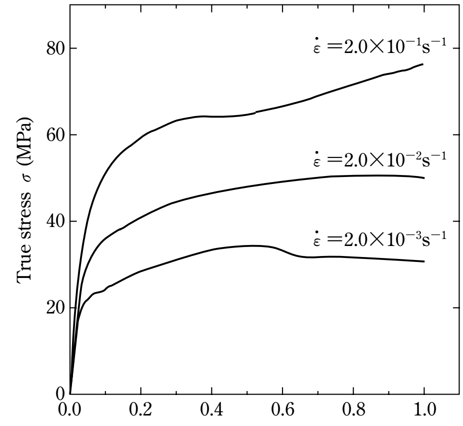

Fig. 7 Flow curves of Cu-0.65Sn-P alloy bicrystal with [011] twist 18° grain boundaries tested in compression at 1,073K at various true strain rates

conditions of strain rate $\dot{\varepsilon}=2.0\times10^{-3}\mathrm{s}^{-1}$ and $2.0\times10^{-1}\mathrm{s}^{-1}$, and a true strain of $\varepsilon=0.2$, 0.5 and 1.0. The samples were water quenched within 1s after the compression to freeze the microstructure. **Fig. 8**[13] shows the result of the OIM observations.

For the strain of $\varepsilon=0.2$, no new-grain was observed to have been formed for any strain rate; however, at a slow strain rate of $\dot{\varepsilon}=2.0\times10^{-3}\mathrm{s}^{-1}$, more significant grain boundary serration was observed to have occurred (Fig. 8 (d)). For the strain of $\varepsilon=0.5$, no dynamically recrystallized grain was observed at the strain rate of $\dot{\varepsilon}=2.0\times10^{-1}\mathrm{s}^{-1}$ (Fig. 8 (b)); however, at $\dot{\varepsilon}=2.0\times10^{-3}\mathrm{s}^{-1}$, dynamically recrystallized grains were observed in the vicinity of grain boundaries (Fig. 8 (e)). For the strain of $\varepsilon=1.0$, the entire region was dynamically recrystallized at $\dot{\varepsilon}=2.0\times10^{-3}\mathrm{s}^{-1}$ (Fig. 8 (f)). On the other hand, for $\dot{\varepsilon}=2.0\times10^{-1}\mathrm{s}^{-1}$, the grain boundary serration is still small, and the dynamic recrystallization has only partially occurred on the grain boundaries and within each grain, resulting in an inhomogeneous structure (Fig. 8 (c)). It is noteworthy that the new grains are formed both on the grain boundaries and inside the parent crystals. Grain boundaries are known to work as preferential formation sites for new grains. Within a grain, on the other hand, deformation zones and the peripheries of precipitates are known to work as preferential nucleation sites of dynamically recrystallizing grains[14), 15)]. It has turned out from the results shown in Fig. 8 that the new grains are formed preferentially on grain boundaries when the strain rate is low and are formed both within grains and on grain boundaries when the strain rate is high. It has also turned out that most of these dynamically recrystallized grains contain twins and multiple twins. This indicates that the dynamic recrystallization behavior is governed by the mechanism of annealing twins, regardless of the high/low strain rate and the difference in the nucleation sites of the dynamically recrystallized grains. In other words, the dynamic recrystallization mechanism is a discontinuous mechanism, in which the subgrain boundaries, formed within parent crystals by old grain boundaries or recovery, migrate, leaving behind twin crystals.

Fig. 9 shows the misorientation between the points shown in Fig. 8 (e) of the 18° bicrystal. From

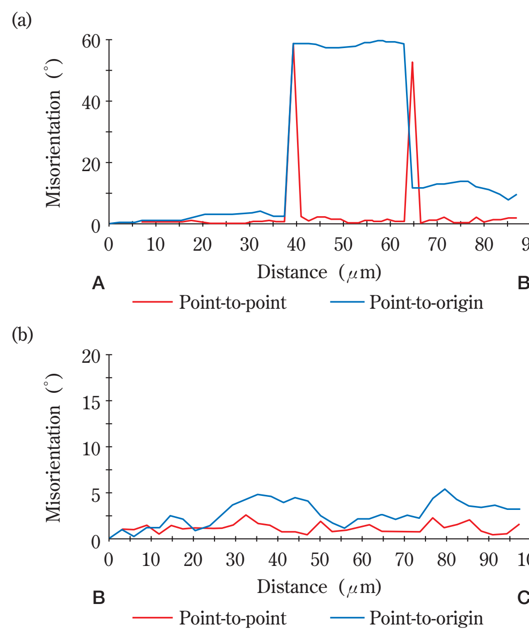

Fig. 9 Change in misorientation change between the points A-B (a) and B-C (b) shown in Fig.8(e)

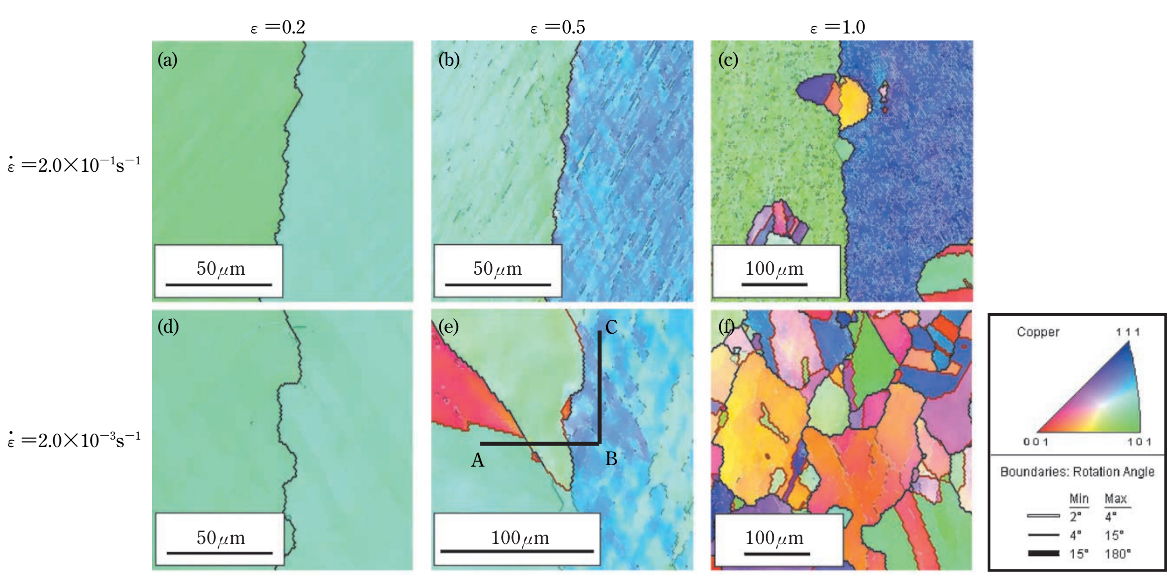

Fig. 8 OIM maps of microstructures in Cu-0.65Sn-P alloy bicrystals having [011] twist 18° grain boundaries deformed to various strains at 1,073K at strain rates of $\dot{\varepsilon}=2.0\times10^{-1}\mathrm{s}^{-1}$ and $\dot{\varepsilon}=2.0\times10^{-3}\mathrm{s}^{-1}$ [13)]

the result of misorientation analysis along A-B, the new grains formed on grain boundaries are found to have a large misorientation of approximately 60 degree, indicating that the new grains have a twin crystal relationship with the parent crystal (Fig. 9 (a)). On the other hand, the misorientation in the parent crystal on the line A-B is approximately 5 degrees at maximum. This implies the formation of substructure by the deformation and recovery. In other words, the cross-slip and climb motion of dislocations during deformation causes the simultaneous generation and annihilation of dislocations. The intracellular dislocation structures are considered to indicate the intragranular formation of subgrains having more regular boundaries.

Similarly, the change in misorientation observed in the matrix along the line B-C was within approximately 5 degrees (Fig. 9 (b)). This implies that the gradual dynamic recovery and crystal rotation by slip deformation are induced continuously inside the parent crystals[16]. This is a feature of continuous dynamic recrystallization. The discontinuous dynamic recrystallization is the most important dynamic recrystallization mechanism that occurs in the present alloy and affects its structural change; however continuous dynamic recrystallization is considered to occur simultaneously, contributing to the formation of the substructure as described above.

4. The effect of the additive amount of Sn on the dynamic recrystallization behavior of materials with a fine grain

4.1 Fine grain polycrystalline material

From the results described in Sections 2 and 3, it has been clarified that the Cu-Sn-P alloy exhibits a dynamic recrystallization behavior almost the same as the one exhibited by the copper alloy most generally used[17]. It has been shown that the annealing twins, formed by grain boundary serrations and behind the migrating grain boundaries, causes the preferential formation of new grains on the grain boundaries and necklace recrystallization of the grains[18]. This fact indicates that the discontinuous dynamic recrystallization caused by the formation of annealing twins becomes the governing mechanism, despite the decrease in dislocation mobility and grain boundary migration brought on by the addition of Sn.

However, no systematic study has been conducted on the effect of the additive amount of Sn on the dynamic recrystallization behavior, in which the additive amount of Sn was as low as less than 1%, as in the case of Cu-Sn-P high strength copper, nor on the effect of the initial grain size. Hence, we have conducted a detailed study as described below.

4.2 Experimental method

The samples tested were Cu-0.66mass%Sn-0.025 mass%P alloy (hereinafter, Cu-0.66Sn-0.025P), the same composition as that of the high strength copper KHRT, and alloys having a higher or lower additive amount of Sn, Cu-0.31mass%Sn-0.024mass%P (hereinafter, Cu-0.31Sn-0.024P) and Cu-1.02mass% Sn-0.025mass%P (hereinafter, Cu-1.02Sn-0.025P). A 99.99% pure copper (hereinafter, 4NCu) was also used as a reference material.

The Cu-Sn-P was melted, casted, hot-rolled and then machined into a round bar. Solid cylinder specimens, each having a diameter of 8mm and height of 12mm, were prepared from this round bar for compression tests. These specimens were vacuum annealed such that they had an equiaxial crystal grain structure with an average grain size of 200μm.

These specimens were compression tested at temperatures of $T = 1{,}073 - 1{,}213$K and strain rates of $\dot{\varepsilon} = 2.0\times10^{-4}\mathrm{s}^{-1} - 2.0\times10^{-1}\mathrm{s}^{-1}$, until the true strain became $\varepsilon = 1.0$. Each specimen was water-cooled within 1s after the compression test. A vacuum, high-temperature compression testing machine (Instron type) was used for the compression test.

4.3 Experimental results and discussion

The specimens of the three Cu-Sn-P alloys with different additive amounts of Sn and 4NCu were compression tested at a strain rate of $\dot{\varepsilon} = 2.0\times10^{-1}\mathrm{s}^{-1}$ and a temperature of $T = 1{,}073$K. The results are shown in **Fig.10**. The 4NCu clearly exhibits work softening, indicating the occurrence of dynamic recrystallization. The work softening is indistinct for the Cu-Sn-P alloys and an increasing amount of Sn enhances this trend. An increasing amount of Sn increases the maximum value of the true stress, with both the peak strain and peak stress shifted towards the high strain side.

Fig.11 shows optical micrographs of the structures obtained by the high temperature compression up to a strain of $\varepsilon = 1.0$, each corresponding to each stress-strain curve in Fig.10. The 4NCu shows dynamically recrystallized coarse grains that are homogeneous and equiaxial, indicating that sufficient dynamic recrystallization occurred throughout the area. On the other hand, the Cu-Sn-P alloys show new grains that are finer than those of the 4NCu. Furthermore, a large portion of the Cu-1.02Sn-0.025P alloy, which contained the largest amount of Sn, remained unrecrystallized (Fig.11(d)). This result indicates an

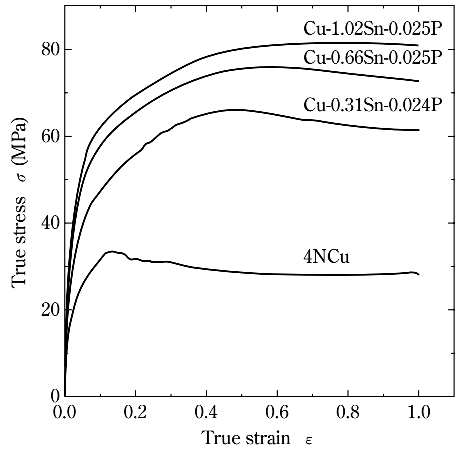

Fig.10 True stress vs. true strain curves of Cu-Sn-P alloys with different Sn content and 4NCu when compressed at $\dot{\varepsilon}$=2.0×10^{-1}s^{-1} at 1,073K

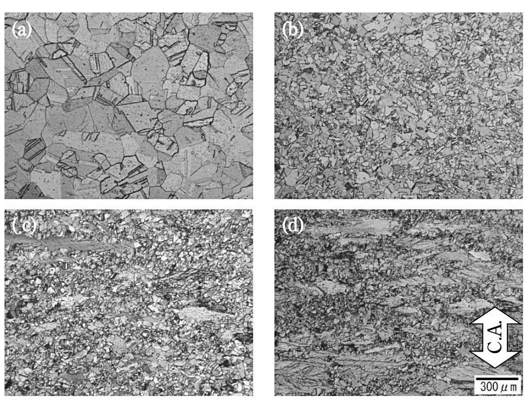

Fig.11 Microstructures in specimens deformed to ε =1.0 at a strain rate of $\dot{\varepsilon}$=2.0×10^{-1}s^{-1} at 1,073K; (a) 4NCu, (b) Cu-0.31Sn-0.024P, (c) Cu-0.66Sn-0.025P, (d) Cu-1.02Sn-0.025P
C.A.：compression axis

insufficient occurrence of dynamic recrystallization. The area of the unrecrystallized region decreases with a decreasing additive amount of Sn. Now, Fig.11 is compared with Fig.6 (a). Despite the slight difference in conditions, it is clear that new grains are more widely generated when the initial structure is finer.

The relationships between the peak stress and peak strain for the Cu-Sn-P alloys and 4NCu reference material were obtained from all the stress-strain curves of the high temperature deformation (**Fig.12**). All of the Cu-Sn-P alloys and 4NCu exhibit almost linear relations regardless of the temperature and strain rate. The slope becomes steeper as the additive amount of Sn increases, with a vast difference between the 4NCu without Sn and the Cu-Sn-P alloys. This clearly shows that the addition of Sn delays the occurrence of dynamic recrystallization in relation to the peak strain. The addition of Sn is considered to have caused a solute drag effect (solute drag resistance) on the dislocation movement, decreasing the recovery and the moving velocity of grain boundaries. This is judged to have caused the delay of dynamic recrystallization and the resulting crystal grain refinement.

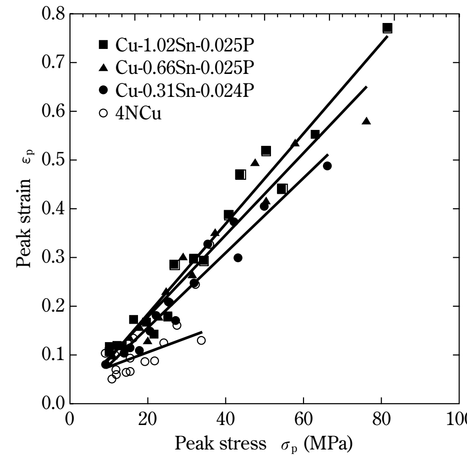

Fig.12 Relationship between peak flow stress and peak strain of Cu-Sn-P alloys and 4NCu

As is clear from the comparison between Fig.5 and Fig.12, the crystal grain refinement facilitates dynamic recrystallization. In other words, the preferential formation of new grains at grain boundaries, clarified in Section 3, promotes the occurrence of dynamic recrystallization even more when the initial crystal grain is finer. This provides the extremely important insight that, by making the initial grain size of the billet material smaller, (1) the flow stress during hot extrusion can be decreased, (2) the extrusion in a lower temperature region at a higher strain rate becomes possible, and (3), as a result, a fine and more homogeneous fine grain structure is obtained.

Conclusions

The present study has clarified a part of the mechanism for dynamic recrystallization behavior in the high strength copper Cu-Sn-P. The following basic knowledge was obtained concerning the deformation behavior and microstructure control of the present alloys during working.

(1) The occurrence of dynamic recrystallization in the cast material of Cu-0.65Sn-P is delayed, compared with that of Cu-P cast material, by the solid solution of Sn, which results in an increase in the maximum value of true stress. This result matches the experience of the extrusion process at the production site.

(2) The dynamic recrystallization behavior of the bicrystal of the Cu-Sn-P alloy depends largely on the strain rate. In other words, when the strain rate is low, new grains are formed

preferentially on the grain boundaries that accompany grain boundary serrations, while, when the strain rate is high, the intragranular formation of new grains is induced by the formation of a slip/shear zone in addition to the formation of the new grains on the grain boundaries.

(3) The dynamic recrystallization behavior has turned out to be governed by the mechanism of annealing twins, regardless of whether the strain rate is high or low and the difference in the formation site of dynamically recrystallized new grains.

(4) The addition of Sn delays the occurrence of dynamic recrystallization and, as a result, increases the peak stress and peak strain of the stress-strain curve. The addition of Sn has caused the refinement of the new grains formed by dynamic recrystallization; however, a large amount of additional Sn limits the occurrence of dynamic recrystallization, which causes a unrecrystallized region to remain.

In areas such as hot extrusion, there is still room for improvement in the high strength copper, when compared with the conventional pure copper, phosphorous-deoxidized copper. It is important to determine the conditions for the process of tube making, with attention to the fundamental knowledge obtained by the present study, giving consideration to the aspects of both workability and microstructure control. It is, furthermore, important that these results be reflected in an improvement in material quality.

It is believed that the achievements of the present study will become an important asset in the alloy extrusion technology at KOBELCO&MATERIALS COPPER TUBE (THAILAND) CO., LTD.

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