Effect of Colony Boundaries on Yield Strength of Al-CuAl₂ Lamellar-Eutectic Composites at High Temperatures*

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In order to clarify the effect of colony boundaries on the high-temperature strength of unidirectionally solidified lamellar-eutectic composites, seven kinds of eutectic Al-CuAl₂ polycrystals with different colony sizes and single crystals without colony boundaries were prepared by unidirectional solidification. Polycrystals consisting of randomly oriented colonies were also prepared by casting. Their yield strengths were compared with each other by means of a compression test at strain rates from 2×10^{-5} to $5 \times 10^{-3} \text{ s}^{-1}$ and at temperatures from 523 to 673 K.

It is found that the yield strength parallel to the growth direction of colonies is higher than that of single crystals, while the strength perpendicular to the growth direction is lower than that of single crystals. The strength for the random case is not much different from that for the perpendicular case. These facts are explained by the constraining effect of colony boundaries on the anisotropic deformation of colonies for the parallel case and by preferential shear deformation in boundary regions for the perpendicular case. The dependence of the yield strength on colony size, strain rate and temperature is also described.

(Received March 16, 1989)

Keywords: high-temperature strength, lamellar eutectic composite, aluminum-copper system, unidirectional solidification, colony boundary, boundary sliding

I. Introduction

Directionally solidified eutectic composites have been considered to be a hopeful candidate for high-temperature structure materials such as turbine blade because of their excellent high-temperature strength and of their excellent thermal stability of microstructure⁽¹⁾⁽²⁾. The arrangement of the strengthening phase and colony boundaries in the composite is highly anisotropic, depending on the fabrication process. The anisotropy is directly reflected on the mechanical properties.

In order to achieve the optimum strength, for some directionally solidified eutectic alloys, single crystals without any colony boundaries have been grown, so that the strengthening phase is oriented parallel to the loading direc-

tion, and they have been applied to practical uses⁽³⁾.

In order to clarify the microstructure-dependence of high-temperature strength, many investigations have been carried out by using eutectic Al-CuAl₂ composite⁽⁴⁾⁻⁽⁶⁾. This composite has advantages for fundamental research in that the specimens with a well controlled microstructure are easily prepared and it is one of the lamellar composites which should be more effective for strengthening than fiber- or dispersion-hardened materials. However, the reported experimental results are significantly dispersed and not yet conclusive.⁽⁶⁾

As possible sources of the discrepancies among the results, differences in lamellar orientation relative to the stress axis, the colony boundary effect and the heat-treatment effect⁽⁷⁾ in addition to the lamellar spacing effect were considered in the previous paper⁽⁴⁾, where two kinds of eutectic Al-CuAl₂ single crystals with different interlamellar spacings and without any colony boundaries were prepared and heat-treated under the same conditions. It was found there that the strength of this material

* This paper was originally published in Japanese in J. Japan Inst. Metals, **52** (1988), 762.

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depends neither on lamellar orientation nor on lamellar spacing and it is pretty isotropic. Therefore, the effects of colony boundary and its orientation may be considered as the possible sources of the discrepancies mentioned above.

In this paper, various kinds of eutectic Al-CuAl₂ polycrystals with different colony sizes were prepared by unidirectional solidification, and the effects of colony size and colony-boundary orientation were investigated.

II. Experimental Procedure

1. Specimen preparation

An eutectic Al-17.3 mol%Cu alloy was melted and cast by using the same method as mentioned in the previous paper⁽⁴⁾. After casting into a cylindrical crucible 20 mm in diameter and 300 mm in height, the alloy was unidirectionally solidified upwards at rates from $2 \times 10^{-1} \text{ cm s}^{-1}$ to $5 \times 10^{-4} \text{ cm s}^{-1}$. In this way, seven kinds of lamellar composites with different colony diameters were made. The colony diameters were 100, 140, 200, 300, 600, 700, and 2000 $\mu\text{m}^\dagger$. In this order, the interlamellar spacings were 0.4, 0.5, 1.1, 1.3, 2.7, 3.4 and 7.6 μm .

From these ingots, specimens were cut out by a diamond cutter so as for the size to be about 4 mm $\times$ 4 mm in cross-section and 6 mm in height. They were finished to the size of 3.0 mm $\times$ 3.0 mm in cross-section and 5.0 mm in height by using the polishing jig reported in the previous paper⁽⁴⁾. The specimens were oriented so that the growth direction of the colonies was parallel or perpendicular to the compression axis. A typical example of the microstructure is shown in Fig. 1. The specimen is seen to have a layer by layer structure composed of α (white) and θ (black) phases and have several colonies elongated to the growth direction.

[†] Here, the term, colony, means the region where the lamellars are parallel. Most of the colony boundaries thus termed, however, seem to be high angle boundaries because of the large differences in lamellar orientation across the boundaries, though the crystallographic orientation of the colonies was not determined.

Fig. 1 Microstructure in a unidirectionally solidified Al-CuAl₂ lamellar eutectic composite.

For comparison, a cast material of eutectic Al-17.3 mol%Cu with randomly oriented colonies (140 μm in colony diameter, 0.5 μm in lamellar spacing) and unidirectionally solidified single crystals without any colony boundaries (5.4 μm in lamellar spacing) were also prepared and tested.

2. High-temperature compression test

The compression test was conducted at various temperatures from 523 K to 673 K under various strain rates from 2×10^{-5} to $5 \times 10^{-3} \text{ s}^{-1}$ by using a Shimadzu-Autograph IS-20T testing machine⁽⁴⁾. The stress-strain curve was measured in the early stage of deformation and the yield stress (0.2% offset stress) was determined as a function of colony size, colony orientation^{††}, strain rate and temperature. The details of the experimental method were the same as those described in the previous paper⁽⁴⁾.

After the test, the microstructure was observed on the specimens by a scanning electron microscope in order to investigate the change in microstructure by the deformation.

^{††} Here, the colony orientation means the colony growth direction relative to the loading direction.

III. Experimental Results

1. Stress-strain curve

Figure 2 shows the stress-strain curve for the deformation slightly over the yield point for the unidirectionally solidified specimens with the parallel orientation as a function of colony diameter D at various temperatures under the same strain rate (Fig. 2(a)), and at various strain rates under the same temperature (Fig. 2(b))^{†††}.

Fig. 2 Stress (σ)-strain (ϵ) curves for unidirectionally solidified Al-CuAl₂ composites compressed parallel to the growth direction; (a) temperature dependence at a strain rate of $3 \times 10^{-4} \text{ s}^{-1}$ and (b) strain rate dependence at 673 K. D : colony diameter.

^{†††} The stress-strain curve up to fracture had quite a similar shape to that of the single crystal reported in the previous paper⁽⁴⁾, for all the kinds of specimens, orientations and temperatures. The curve showed a remarkable work-hardening at the early stage of deformation and then softening. The peak flow stress was observed at about 0.7% plastic strain.

Fig. 3 Stress (σ)-strain (ϵ) curves for unidirectionally solidified Al-CuAl₂ composites compressed perpendicular to the growth direction; (a) temperature dependence at a strain rate of $3 \times 10^{-4} \text{ s}^{-1}$ and (b) strain rate dependence at 673 K. D : colony diameter.

The curves for the perpendicular orientation are shown in Fig. 3(a) and (b). For both orientations, the normal temperature and strain-rate dependence of the flow stress is seen. The strain rate dependence is stronger for the parallel orientation than for the perpendicular orientation. Above $D = 600 \mu\text{m}$, the curve becomes almost independent of colony size under all the test conditions.

It is well known that the colony size decreases along with lamellar spacing as the solidification rate increases⁽⁵⁾⁽⁸⁾. This was also true of the present experiment. Accordingly, the effect of colony size on the curves in Figs. 2 and 3 might include the effect of lamellar spacing, i.e., the observed effect might be the combined effect of colony size and lamellar spacing. As mentioned in the previous paper⁽⁴⁾, however, the stress-strain curve of single

crystals is almost independent of lamellar spacing and lamellar orientation under a wide range of experimental conditions. Therefore, the colony size dependence of the stress-strain curve in Figs. 2 and 3 should not significantly include the effect of lamellar spacing.

From these results, we can presume that the effect of colony boundaries was one source of the discrepancies mentioned in chapter I.

2. Dependence of yield stress on colony size, temperature and strain rate

Figure 4 shows the colony size dependence of yield stress $\sigma_{0.2}$ (0.2% offset stress) at various temperatures for the parallel and perpendicular orientations obtained at a strain rate of $3 \times 10^{-4} \text{ s}^{-1}$. It is found from this figure that $\sigma_{0.2}$ increases as D decreases for both orientations. The D -dependence is strong below about $600 \mu\text{m}$, but very weak above that colony size. The critical size dividing the two size-regions decreases as temperature rises. Figure 5 shows the strain rate dependence of the colony-size effect at 573 K and 673 K. For both orientations, the yield stress tends to decrease with the decrease in strain rate and the critical colony size in parallel tends to decrease. For perpendicular orientation the size dependence

Fig. 4 Colony size (D) dependence of yield stress, $\sigma_{0.2}$, for unidirectionally solidified Al-CuAl₂ composites compressed at a strain rate of $3 \times 10^{-4} \text{ s}^{-1}$. The compression direction is (a) parallel to and (b) perpendicular to the growth direction. L : side length of square cross-section of specimen.

Fig. 5 Colony size (D) dependence of $\sigma_{0.2}$ for unidirectionally solidified Al-CuAl₂ composites compressed at various strain rates at 573 and 673 K. The compression direction is (a) parallel to and (b) perpendicular to the growth direction. L : side length of square cross-section of specimen.

is weak, and at 673 K where the yield stress becomes very low the D -dependence almost disappears in the whole size region.

Figure 6 shows the temperature dependence of yield stress of unidirectionally solidified specimens compared with those of cast polycrystals with randomly oriented colonies and of single crystals without any colonies. Here, the unidirectionally solidified specimens have a colony size of $140 \mu\text{m}$, the size is situated in the region of a strong colony-size effect. The cast specimens have almost the same colony size (the lamellar spacing is also almost the same). The data for single crystals were obtained for the parallel orientation as to the lamellae.

Although the yield stress of the cast specimens is the lowest except at 523 K. It is, however, not much different from that for perpendicular orientation. The yield stress for the parallel orientations is the highest. The

Fig. 6 Temperature dependence of $\sigma_{0.2}$ for unidirectionally solidified Al-CuAl₂ polycrystals, single crystals and cast polycrystals compressed at a strain rate of $3 \times 10^{-4} \text{ s}^{-1}$. The compression direction for the unidirectionally solidified polycrystals is (●) parallel to and (▲) perpendicular to the growth direction.

single crystal is stronger than the perpendicular and random orientations, but weaker than the parallel orientation. This order of strength is independent of temperature. The parallel orientation is several times as strong as the perpendicular orientation.

From the fact that the strength of single crystals is highly isotropic⁽⁴⁾, the strength in the colonies should be almost independent of the lamellar orientation. Then, we can presume that the observed order of strength is the direct reflection of the colony boundary effect: the colony boundaries contribute to increase the strength when the boundaries are parallel to the stress axis, but to decrease the strength when the boundaries are inclined to the stress axis.

Since cast materials may be of practical importance because of its easiness in manufacturing, the strength of the cast specimen is adopted as the standard for evaluating the strength of the unidirectionally solidified specimens. The relative strength is shown in Fig. 7. It is seen that for both orientations the improvement of strength due to unidirectional solidification becomes more effective as temperature rises.

It is well known that a power law relationship holds between strain rate $\dot{\epsilon}$ and stress σ for

Fig. 7 Temperature dependence of $\sigma_{0.2}$ of unidirectionally solidified polycrystals normalized by $\sigma_{0.2}^{\text{cast}}$ of cast polycrystals.

high-temperature deformation of metals⁽⁹⁾. This relationship holds also in the present composites as shown in Figs. 8, 9 and 10.

Thus,

$$\dot{\epsilon} \propto \sigma^n, \quad (1)$$

where the stress exponent n depends on the presence of colony boundaries their orientation and size, and temperature in a complicated manner. The value of n for parallel orientation strongly depends on temperature, ca. 9.5 at 573 K and ca. 4.7 at 673 K, but does not depend on the colony size, while n for the perpendicular orientation increases with the increase in colony size and the size dependence is more pronounced at 673 K than at 573 K. As a result, for $D=2000 \mu\text{m}$, n at 573 K happens to be almost the same as n at 673 K. Further the temperature dependence of n is the strongest for the cast specimens and the weakest for the single crystals. The value of n for perpendicular orientation decreases along with colony size at both temperatures, and finally approach the value for the cast specimens.

The power law relationship mentioned above has been reported to hold also for the steady-state deformation of the Al-Cu eutectic composite⁽⁵⁾⁽¹⁰⁾. However, the reported stress exponent does not always consistent with the present n . This discrepancy may be due to the difference in the colony size and orientation, as

Fig. 8 Strain-rate dependence of $\sigma_{0.2}$ for unidirectionally solidified Al-CuAl₂ composites with various colony sizes at 573 and 673 K. The compression direction is parallel to the growth direction of the colonies. D : colony diameter.

Fig. 9 Strain-rate dependence of $\sigma_{0.2}$ for unidirectionally solidified Al-CuAl₂ composites with various colony sizes at 573 and 673 K. The compression direction is perpendicular to the growth direction. D : colony diameter.

well as the difference in the deformation stage: the present n 's were obtained at 0.2% plastic strain, Transient stage, and not at the steady-state stage. However, the effect due to the difference in the deformation stage may be not so large, because the value of $n=7.2$ has been reported in the creep deformation of single crystals without any colonies⁽¹⁰⁾. This value of n is not much different from 5.7–6.8 for the present single crystals.

Moreover, the behaviour that the value of n for the unidirectionally solidified specimens is always larger than that for the cast specimens has also been reported for the creep deformation of Al-CuAl₂⁽⁵⁾ as well as some other eutectic alloys such as Mg-Al₁₂Mg₁₇⁽¹¹⁾, Co-CoAl⁽¹²⁾ and Ni-Cr⁽¹³⁾. This behaviour is thought to be common in the lamellar eutectic composites.

From the above results, it has been clarified

Fig. 10 Strain-rate dependence of $\sigma_{0.2}$ for cast polycrystals and single crystals of Al-CuAl₂ at 573 and 673 K.

that the colony boundaries strongly affect the strength of lamellar eutectic composites.

IV. Discussion

1. Anisotropy in yield strength

In spite of that the strength of single crystals is almost independent of lamellar orientation, i.e., almost isotropic, as reported in the previous paper⁽⁴⁾, the strength of unidirectionally solidified specimens with colony boundaries shows a strong anisotropy: the parallel orientation shows a much higher strength than that of the perpendicular orientation. The strength of parallel orientation is even higher than that of single crystals without colony boundaries. This strengthening effect due to the colony boundaries can be explained as follows.

As reported in the previous paper⁽⁴⁾, at 0.2% plastic strain of single crystal composites, the strain in the α -phase is mostly plastic, whereas the strain in the θ -phase is mostly elastic. Taking the coordinate axes x , y and z as shown in Fig. 11, the z -axis being parallel to the compression axis and the x - and y -axes perpendicular to the z -axis, the x - and y -axes lie parallel and perpendicular to the lamellar plane, respectively. The strain in the x -direction, ϵ_{xx} , is considered almost the same in both phases⁽⁴⁾, because the constraining effect at the interface between the phases is presumably very strong. Thus,

Fig. 11 Illustration of the coordinates chosen for lamellar composites.

$$\epsilon_{xx} = \epsilon_{xx}^{\alpha} = \epsilon_{xx}^{\theta}, \quad (2)$$

where the superscripts α and θ means the parameters in the α - and θ -phases, respectively[†].

If V_{α} and V_{θ} denote the volume fractions of the α - and θ - phases respectively, the strain in the y -direction is given by

$$\epsilon_{yy} = \epsilon_{yy}^{\alpha} V_{\alpha} + \epsilon_{yy}^{\theta} V_{\theta}. \quad (3)$$

Since the compression axis is parallel to the z -axis, the strain in the z -direction is

$$\epsilon_{zz} = \epsilon_{zz}^{\alpha} = \epsilon_{zz}^{\theta}. \quad (4)$$

When no constraining exists around the crystal, $\sigma_{yy}^{\alpha} = \sigma_{yy}^{\theta} = 0$. Assuming that the strain in the θ -phase is mostly elastic, we obtain

$$\begin{aligned} \epsilon_{xx}^{\theta} &= \frac{1}{E_{\theta}} (\sigma_{xx}^{\theta} - \nu_{\theta} \sigma_{zz}^{\theta}) \\ \epsilon_{yy}^{\theta} &= \frac{-\nu_{\theta}}{E_{\theta}} (\sigma_{zz}^{\theta} + \sigma_{xx}^{\theta}), \end{aligned} \quad (5)$$

where E is the Young's modulus and ν is the Poisson's ratio. Because $\sigma_{xx}^{\alpha} V_{\alpha} + \sigma_{xx}^{\theta} V_{\theta} = 0$ under the unconstraining condition in x - and y -directions and $V_{\theta} = 0.477$,

$$\sigma_{xx}^{\theta} = -\frac{V_{\alpha}}{V_{\theta}} \sigma_{xx}^{\alpha} = -1.1 \sigma_{xx}^{\alpha}. \quad (6)$$

Here $|\sigma_{zz}^{\alpha}| \ll |\sigma_{zz}^{\theta}|$, because the flow stress in the α -phase is much smaller than the strength of the θ -phase⁽⁴⁾. Further, from the fact that the strain in the α -phase is mostly plastic $|\sigma_{xx}^{\alpha}| \leq |\sigma_{zz}^{\alpha}|$. Thus, $|\sigma_{zz}^{\theta}| \gg |\sigma_{xx}^{\alpha}| \cong |\sigma_{xx}^{\theta}|$ (refer to eq. 6). Then, we obtain with a good approximation

$$\epsilon_{xx}^{\theta} = \epsilon_{yy}^{\theta} = -\frac{\nu_{\theta}}{E_{\theta}} \sigma_{zz}^{\theta} = -\nu_{\theta} \epsilon_{zz}^{\theta}. \quad (7)$$

Since the strain in α -phase is plastic,

$$\epsilon_{yy}^{\alpha} = -(\epsilon_{zz}^{\alpha} + \epsilon_{xx}^{\alpha}). \quad (8)$$

From these equations mentioned above, we obtain

[†] ϵ_{ii} and σ_{ii} ($i=x, y, z$) are referred hereafter to as the tensile strain and tensile stress in the i -direction, respectively.

$$\frac{\varepsilon_{yy}}{\varepsilon_{xx}} = \frac{1}{\nu_\theta} [(1 - \nu_\theta) V_\alpha + \nu_\theta V_\theta]. \quad (9)$$

Here, $V_\alpha (= 1 - V_\theta)$ is 0.523 and ν_θ is assumed to be $1/3$. Then, $\varepsilon_{yy}/\varepsilon_{xx} = 1.52$, i.e., the strain in the y-direction perpendicular to the lamellar plane is about 1.5 times as large as that in the x-direction parallel to the lamellar plane.

From this large strain-anisotropy, a strong constraining to deformation may occur in each colony in a unidirectionally solidified specimen of parallel orientation. This is illustrated in Fig. 12(a), where the arrows indicate the direction of the displacement and its relative magnitude by their length. This constraining effect is thought to be the reason why the parallel orientation is stronger than single crystals without colony boundaries.

On the other hand, for the specimens of perpendicular orientation, there are colony boundaries inclined to the stress-axis and the shear deformation occurs preferentially along the boundaries, as illustrated in Fig. 12(b), because there exists a soft layer along a boundary, where the lamellar structure is destroyed⁽¹⁴⁾⁻⁽¹⁶⁾. This is thought as being the reason why the perpendicular orientation is much weaker than the single crystal.

As described above, the strength of unidirectionally solidified specimens is understandable as the effect of colony boundaries.

Fig. 12 Schematic representation of the deformation of lamellar composites with aligned colonies, showing compression (a) parallel to and (b) perpendicular to the growth direction.

2. Effect of colony size on yield strength

As shown in Figs. 4 and 5 and Figs. 8 and 9, the yield strength depends on the colony size. If the eutectic lamellar composite consisting of a lot of colonies deforms as shown in Fig. 12, the constraining effect is not the same in the interior and surface regions of the specimens: the effect should be weaker in the surface region than in the interior region. For the same cross-section, the relative number of colonies in the surface region decreases as the colony size decreases, and the surface effect on the strength decreases.

The abscissa shown on the upper side in Figs. 4 and 5 is the ratio of the colony diameter, D , to the side length in the cross-section, L . The minimum value of D/L is about 0.03 in the present experiment and the colony size dependence in the figures is thought to be strongly affected by the surface effect. The surface effect may be removed by extrapolating the value of D/L to zero. In this case, however, it remains difficult to understand the structure of infinitesimally small colony size. Here, we adopt the extrapolated value by assuming that the observed colony-size dependence mainly comes from the surface effect. Thereby it is supposed that the difficulty of the infinitesimal colony-size can be avoided, because the temperature and strain rate dependence of the extrapolated value is almost the same as that of the specimen with $D/L = 0.03$. And thus the extrapolated value is expected to correspond nearly to the structure of the smallest colony size.

As seen in Figs. 4 and 5, for the extrapolated values the parallel orientation is always stronger than the perpendicular orientation. This difference comes from the difference in the effect of colony-boundaries illustrated in Fig. 12.

3. Temperature and strain-rate dependence of yield strength

As shown in Fig. 10, the stress exponent n in single crystals is temperature-insensitive and about 6.2. On the assumption of Arrhenius-type temperature-dependence of the strain rate, we obtain $\dot{\varepsilon} \propto \sigma_{0.2}^n \exp(-Q/RT)$, where

Q is the activation energy for deformation, T the absolute temperature and R the gas constant. For single crystals the activation energy was estimated to be about 150 kJ/mol from the temperature dependence of strain rate under a constant $\sigma_{0.2}$.

Proulx and Durand⁽¹⁷⁾ obtained almost the same activation energy for single crystals by means of the compression-creep test. On the other hand, Schmidt-Whitley obtained 218 kJ/mol for unidirectionally solidified specimens with colonies, and 221 and 146 kJ/mol for the θ - and α -(containing Cu in solution) single phase materials, respectively, by means of the tensile creep test. He concluded that the deformation of the composite was controlled by that of θ -phase, because their activation energies are very close to each other.

On the other hand, Ignart and Durand⁽¹⁰⁾ obtained 93 kJ/mol above 573 K and 220 kJ/mol below 573 K for single crystals by means of the tensile creep test. From this result together with the transmission electron microscopic observation⁽¹⁸⁾, they concluded that the deformation of the composite was controlled below 573 K by the deformation of α -phase and above 573 K by the deformation of the θ -phase. Further, they considered the reason why the activation energy obtained by Proulx and Durand was as high as 150 kJ/mol in spite of the data having been obtained in the lower temperature region where the deformation of the composite is controlled by that of the α -phase, and inferred that the creep stress adopted by Proulx and Durand was so low that the dislocation-climb controlled the deformation (the high-temperature-type deformation of the α -phase).

Although the deformation stage at which the activation energy was obtained is different, say, at 0.2% plastic strain in the present experiment and in the steady-state stage in the referred experiments, the activation energy obtained in the present experiment is very close to that for compression-creep obtained by Proulx and Durand and that in the α single phase material by Schmidt-Whitley. Accordingly, the deformation at 0.2% plastic strain is presumed to be controlled by the plastic deformation of the α -phase. The temperature-

Fig. 13 Relation between temperature-compensated strain-rate and yield stress, $\sigma_{0.2}$, for Al-CuAl₂ composites with various internal-structures. The yield stresses for the unidirectionally solidified composites are the extrapolated values to infinitely small colony size.

compensated strain rate, $\epsilon \exp(Q/RT)$, is calculated by using 150 kJ/mol for Q , which is obtained for single crystals (Fig. 10), and plotted against the yield stress $\sigma_{0.2}$ in Fig. 13. The datum points lie well on straight lines independent of temperature.

If the deformation is controlled by the same process in all the specimens used in the present experiment, it is to be expected that the slope of the lines obtained by using the activation energy for the single crystal should be the same for all the specimens (the same stress exponent). For the directionally solidified specimens with colonies, the extrapolated values are used in Fig. 13. For the cast material, the data in Fig. 10 are directly used, because the colony size was not varied.

As seen in Fig. 13, there is a bending point on the line for the cast material and for the perpendicular orientation of the unidirectionally solidified material. In the higher stress region above the bending point, the slopes of the lines are almost equal to that for the single crystal. Therefore, in the higher stress region the deformation is controlled by the same process in all the materials.

The same slope, together with the same activation energy equal to that in α single phase material, indicates that the deformation is controlled by the deformation of the α -phase in-

side the colonies or in colony boundaries for all the materials used.

However, the temperature-compensated strain rate is higher in the order of random orientation (cast material), perpendicular orientation, single crystal, and parallel orientation. As shown previously, the parallel orientation is the strongest, even stronger than the single crystal, because of the constraining effect of colonies, and the strain rate is the lowest. The higher strain rate for the perpendicular and random orientations comes from the preferential shear deformation along the colony boundaries. The strain-rate order is the same as the order of the strength.

On the other hand, the slope in the lower stress region for the random and perpendicular orientations is much more gentle. This slope-change is well known in metals where the slope, n , for the creep deformation decreases in the low stress region when the boundary sliding dominates⁽¹⁹⁾. Schmidt-Whitley also observed that n obtained by tensile creep of the unidirectionally solidified materials changed from $n \cong 6$ in the higher stress region to $n = 2$ in the lower stress region and he explained in the following way, relating this slope-change to the size of subgrains formed in the α -phase. He thought that the high value of n in the higher stress region comes from the stress dependence of the subgrain size which is smaller than the width of the α -phase lamellae, as is usually observed in pure metals, while the low value of n comes from the stress-independent subgrain size, which is limited by the width of α -phase lamellae. He assumed that the deformation is controlled by recovery in the higher stress region, while the deformation is controlled by the disappearing process at the α - θ interfaces of the dislocations in the subgrains in the lower stress region. His idea was supported by the observation of phase-boundary sliding⁽²⁰⁾. However, the phase-boundary sliding is presumably not so significant at least up to 0.2% plastic strain because the 0.2% proof stress of the single crystal depends neither on lamellar spacing nor on lamellar orientation, as reported in the previous paper⁽⁴⁾.

Moreover, the value of n for random orientation (cast material) is as small as about 2 even

Fig. 14 Scanning electron micrograph of a cast specimen compressed at 673 K to 28.6%, showing colony-boundary sliding.

though the colony size and lamellar spacing in the cast material are almost the same as those in the unidirectionally solidified material. The lower n for random orientation than that for the perpendicular orientation probably comes from the fact that the number of the colony boundaries suffering a high shear stress is more than that for the perpendicular orientation.

Therefore, the mechanism proposed by Schmidt-Whitley for the lower stress region probably control the deformation along the colony boundaries. Thus, the deformation of the composite is believed to be controlled by a combined mechanism of the preferential deformation in the soft region along the colony boundaries and the colony-boundary sliding.

Figure 14 is a scanning electron micrograph of the cast specimen compressed up to 28.6% at 673 K. The colony boundaries are seen as white lines, showing that steps have been formed at the colony boundaries. The step-formation indicates that a very large shear deformation has occurred at the colony boundaries. It has been reported that the colony-boundary sliding was observed in the crept cast material (random orientation) but not observed in the unidirectionally solidified material crept parallel to the colony boundaries⁽⁵⁾.

V. Conclusion

In order to clarify the effect of colony boun-

daries on the high-temperature strength of unidirectionally solidified lamellar eutectic composite, seven kinds of eutectic Al-CuAl₂ composites with different colony sizes and single crystals without colony boundaries were prepared by unidirectional solidification. The colonies elonged in the growth direction, and specimens with parallel and perpendicular orientations of colonies to the stress axis were prepared. Composites with randomly oriented colonies were also prepared by casting. Their yield strength was compared with one another by means of the compression test at strain rates from 2×10^{-5} to $5 \times 10^{-3} \text{ s}^{-1}$ and at temperatures from 523 to 673 K. The results obtained are as follows.

(1) For both orientations the yield stress (0.2% proof stress) increased as the colony size decreased. However, the colony-size dependence was considered to arise from the surface effect due to the limited specimen size and not to the true colony size dependence.

(2) The yield stress for the parallel orientation was considerably higher than that of single crystals, whereas that for the perpendicular orientation is considerably weaker than the single crystals. The strengthening effect of colony boundaries was explained by the constraining effect of colonies on deformation, and the weakening effect of colony boundaries, by the preferential shear deformation along colony boundaries.

(3) From the stress exponent of strain rate and the activation energy for deformation, it was inferred that the deformation of the composite was controlled by the deformation in the α component phase existing in the lamellae and along the colony boundaries in the whole stress range tested for the single crystals and the parallel orientation and in the higher stress region for the perpendicular and random orientations, while the deformation in the lower stress region was controlled by the colony-boundary sliding for the perpendicular and random orientations.

(4) Therefore, it is concluded that in the unidirectionally solidified materials with colonies, aligning the colony boundaries parallel to the loading direction was very important for the practical use. The strong anisotropy in the

strength contrasts the highly isotropic strength of single crystals without colony boundaries.

Acknowledgments

The authors would like to thank Mr. S. Yamashita (Graduate School Student, Present address: Yasukawa Electric MFG. Co., Ltd.) for his cooperation in the experiment. This work was financially supported by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan and by Light Metal Educational Foundations from Japan Light Metal Association. They are very much appreciated.

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