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Comparison of Phosphor Bronze Metal Sheet Produced by Twin Roll Casting and Horizontal Continuous Casting

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Much effort recently has been expended to study the strip casting process used to produce thin metal strip with a near final thickness. This process eliminates the need for hot rolling, consumes less energy, and offers a feasible method of producing various hard-to-shape alloys. The finer microstructure that results from the high cooling rate used during the casting process enhances mechanical properties. In this study, strips of phosphor bronzes (Cu-Sn-P) metal were produced using a twin roll strip casting process as well as a conventional horizontal continuous casting (HCC) process. The microstructures, macrosegregations, textures, and mechanical properties of the as-cast and as-rolled metal sheet produced by these two methods were examined carefully for comparative purposes. The results indicate that cast strip produced by a twin roll caster exhibit significantly less inverse segregation of tin compared to that produced by the HCC process. The mechanical properties including tensile strength, elongation, and microhardness of the products produced by the twin roll strip casting process are comparable to those of the HCC processed sheet. These properties meet specifications JIS H3110 and ASTM B 103M for commercial phosphor bronze sheet. The texture of the as-rolled sheet from these two processes, as measured from XRD pole figures, were found to be virtually the same, even though a significant difference exists between them in the as-cast condition.

Keywords continuous casting, Cu-Sn-P alloys, phosphor bronze

1. Introduction

In the commercial production of copper and copper alloy sheet, direct chill (DC) casting, also known as semicontinuous casting, is used widely to produce metal ingots, which then are shaped into strip or sheet via subsequent hot and cold rolling procedures. This process has many advantages, including superior quality, excellent flexibility of ingot dimensions, and high production yield. However, due to the inverse segregation of Sn and P, it is not suitable to produce phosphor bronze (Cu-Sn-P) ingots by direct chill casting. The Sn- and P-rich regions near the ingot surface are susceptible to the problems of hot tears and hot cracks during the subsequent hot rolling process. For this reason, an improved process, the horizontal continuous casting (HCC) system, has been used widely to cast phosphor bronze plate (Ref 1). The maximum plate width of approximately 800 mm plus the relatively low casting speed of approximately 0.2 to 0.4 m/min associated with this process result in low productivity per strand. Additionally, microporosity on the cast surface of HCC plate is another serious problem that can cause cracking during cold rolling. This type of microporosity is related to isolated areas of poorly fed shell for the later solidification close to the cast surface. Because this type of porosity defect is located near the surface, a layer of material about 1 mm thick is usually milled from the cast surface prior to the rolling operation. This milling process eliminates cracking of the milled product; however, it lowers the production yield of the material, thus leading to increased cost. Nonetheless, milling ensures the surface quality of the final product, which is of primary importance for electronic connector applications.

Because of the afore-mentioned drawbacks to the HCC process, constant efforts are underway to improve metal processing technology. Strip casting has been recognized as a cost-effective method of producing a wide variety of flat rolled products (Ref 2, 3). In this process, a metal strip or sheet with a thickness of less than 6 mm is cast directly from the molten liquid without hot rolling. Strip casting has evolved into an innovative technology of continuous casting for producing near-net shape products. The benefits of lower capital investment and operational costs associated with this process have stimulated increasing efforts to develop this casting technology worldwide (Ref 4). During the last two decades, many materials have been cast successfully using the strip casting technique, such as stainless steel (Ref 5, 6), high-silicon steel (Ref 7, 8), as well as copper and copper alloys (Ref 9-11). It is thus believed that this continuous casting process is suitable for producing bronze or phosphor bronze plate without experiencing low productivity and the surface defects that usually occur with conventional HCC processing. Gellenbeck et al. (Ref 9) used an unequal twin roll caster to produce thin copper alloy strip. They found that significant cost reduction could be achieved with this process compared to the HCC or DC process. Roller et al. (Ref 10) cast a number of copper and copper alloys ($CuSn_6$ and $CuZn_{30}$) with the single-belt process, also known as the direct strip casting (DSC) process, at Wieland AG in Vöhringen. Cast strip with a thickness of 5 to 10 mm was further processed in the conventional manner, i.e., surface milling and cold rolling. The resultant products met the normal physical property requirements.

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Essadiqi et al. (Ref 11) also investigated the characteristics of Cu-Ni-Sn and Al-Si-Cu alloys produced with a horizontal twin roll caster. The microstructures and microsegregations of these two alloys were well characterized.

The objective of the present study was to investigate the major differences between phosphor bronze (C5191) sheet produced using a horizontal twin roll caster and those produced by the HCC process. Strip with a width of 100 mm and thickness of 4.5 mm were produced in a laboratory twin roll caster. Plate with much larger dimensions (15 to 20 mm thick) produced by the HCC process were obtained from a local mill. Evaluation and analysis of the microstructures, macrosegregation, x-ray diffraction, and textures of the two types of resulting materials were conducted. Additionally, the mechanical properties of these materials were also examined and compared with the specification of commercial phosphor bronze sheet, i.e., JIS H3110 and ASTM B 103M (Ref 12, 13).

2. Experimental Procedure

Figure 1 is a schematic diagram of the laboratory horizontal twin roll caster used in the present study. Both rolls are 400 mm in diameter, 100 mm in width, and are made from a chromium-copper alloy. A horizontal nozzle was used to allow the molten metal to flow into the caster in a smooth and nonturbulent manner. Surface quality of the cast strip was ensured by a stabilized melt pool within the setback region during casting, which can be achieved by maintaining a constant level of molten metal inside the tundish. Table 1 indicates the specifications of the twin roll caster and the casting conditions.

During casting, the molten phosphor bronze metal was poured from a transport ladle to a tundish. It then flowed through a horizontal nozzle into a wedge-shape space between the two opposite rotating rolls, which were water cooled internally. Two thin, solidified metal shells immediately formed on the surfaces of the two rolls as the molten metal came in contact with the rolls. These two solid shells gradually grew in thickness as they moved with the rotating rolls. Eventually, the two shells came in contact with each other and welded together at a position slightly behind the roll bite point (closest position between two rolls). The dummy sheet, which was first inserted between the rolls before casting, was then removed carefully and a solidified strip followed continuously. The cast strip was reduced from the initial thickness of 4.5 mm to the final gage of 0.3 mm, with several subsequent cold rolling and annealing procedures, as indicated in Fig. 2. With the other process, a thicker plate (15.6 mm thick and 480 mm wide) of phosphor bronze metal was fabricated with HCC equipment in a local copper mill. The HCC equipment consisted of high-density graphite molds, the inner surfaces of which were polished to reduce friction. Heat was extracted from the mold by a water-cooled copper cooler. The thickness of the cast plate was reduced to the final gage of 0.2 to 0.5 mm after surface milling and a series of cold rolling and annealing procedures.

The chemical compositions of the two groups of cast materials are given in Table 2, in which plate A and plate B denote the materials produced by the twin roll strip casting and the HCC processes, respectively. Note that the chemical compositions of both groups are within the standard specifications for C5191 alloy. The microstructures of plate A and plate B were prepared for examination with the following etching solutions: (a) as-cast materials: 5 g $Fe(NO_3)_3$ + 25 ml HCl + 7 ml H_2O and (b) cold rolled and annealed materials: 2 g $KCrO_3$ + 3 ml H_2SO_4 + 50 ml H_2O.

Studies of as-cast macrosegregation in both materials were conducted by performing a series of chemical analyses on the

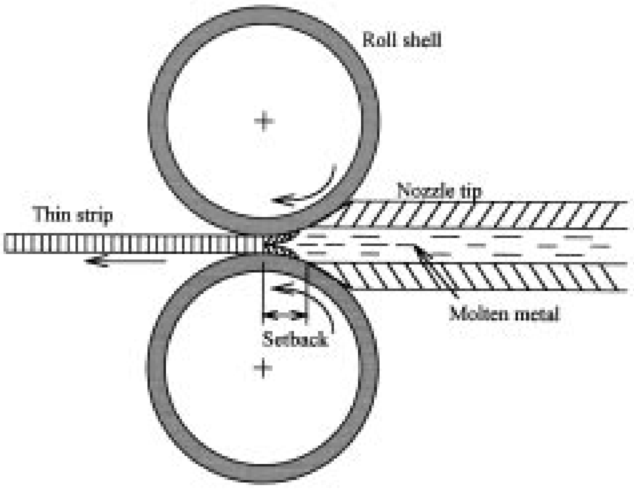


Fig. 1 Schematic of the horizontal twin roll strip caster system

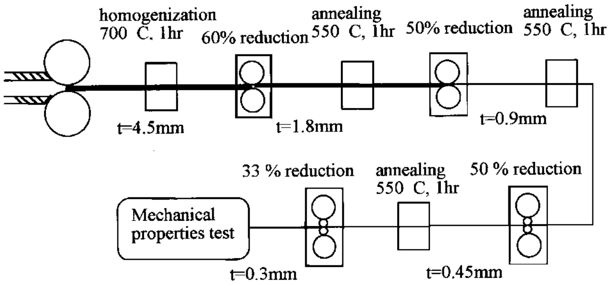


Fig. 2 Rolling and annealing procedures used to produce the twin roll cast phosphor bronze sheet

Table 1 Apparatus specifications and process conditions

Casting material	Phosphor bronze (C5191)
Roll dimension	400 mm (diam) × 100 mm (width)
Roll gap	4.5 mm
Roll material	1%Cr-Cu
Casting speed	12 to 24 m/min
Setback	70 to 100 mm
Pouring temperature	1045 to 1070 °C

Table 2 Chemical compositions of phosphor bronze (C5191)

Chemical composition, %	Sn	P	Cu+Sn+P
Plate A (strip cast)	6.28	0.173	99.8
Plate B (HCC)	6.23	0.14	99.7
Standard specification (C5191) JIS	5.5 to 7.0	0.03 to 0.35	>99.5

metal chips that were removed layer by layer from the surface to the center of the two plates. The chips were collected after sequentially removing a 0.1-mm thick layer of material from the cast plate and then were examined with the ICP-AES method. The x-ray diffraction patterns were obtained using a PHILIPS PW 1700 diffractometer with Cu-Kα radiation (λ = 1.5406 Å). Hardness measurements and tensile tests along the rolling direction of the final products (H grade sheet) were also performed. The results of the tests were compared with JIS H3110 and ASTM B 103M specifications for commercial phosphor bronze sheet. The crystallographic textures of the as-cast plate and the sheet from the two processing conditions were measured with a Siemens D-500 x-ray diffractometer with Mo-Kα radiation (λ = 0.71 Å) . The incomplete (111) pole figure was recorded for each texture with the Schulz back-reflection method (Ref 14).

3. Results and Discussion

3.1 Solidification Structure

Figure 3 shows the solidification structure of the transverse cross section of the cast strip (plate A) produced by the twin roll caster. The optimized conditions for casting the strip were as follows:

- Setback = 80 mm
- Roll gap = 4.5 mm
- Casting speed = 15 m/min
- Counter force for roll separating = 1 ton
- Temperature of pouring = 1065 °C

It is known that the liquidus (T_L) and the solidus (T_S) temperatures of phosphor bronze (C5191) are 1045 and 910 °C, respectively.

As shown in Fig. 3, an inner fine equiaxed zone and two outer coarse equiaxed zones are clearly visible. The average grain sizes in the coarse and fine equiaxed zones are approximately 80 and 34 μm, respectively. The relatively coarse equiaxed grains visible in the outer region contrast vividly with the columnar dendritic structures that are generally observed in stainless steel strip cast by the same twin roll caster (Ref 15). This phenomenon can be explained as follows. Because the contact arc time of the melt and the roll is very short (t_c = 0.32 s) during casting, the nucleated grains that form near the surface do not have sufficient time to grow directionally along the radial heat flow direction. Additionally, the dendrite arms are more likely to be broken by the melt flow within the setback region in the relatively large mushy zone of phosphor bronze (about 135 °C), thereby forming numerous nuclei. Both of the above-mentioned factors jointly favor the formation of coarse equiaxed grains instead of columnar structures. On the other hand, a fine grain zone is present in the central region of the cast strip, where the cooling rate is lower than that in the surface regions. Formation of fine grains is believed to be induced by the solute enrichment and the associated constitutional supercooling that occur in the region during the later stage of solidification. This is verified by the chemical analysis discussed in Section 3.2.

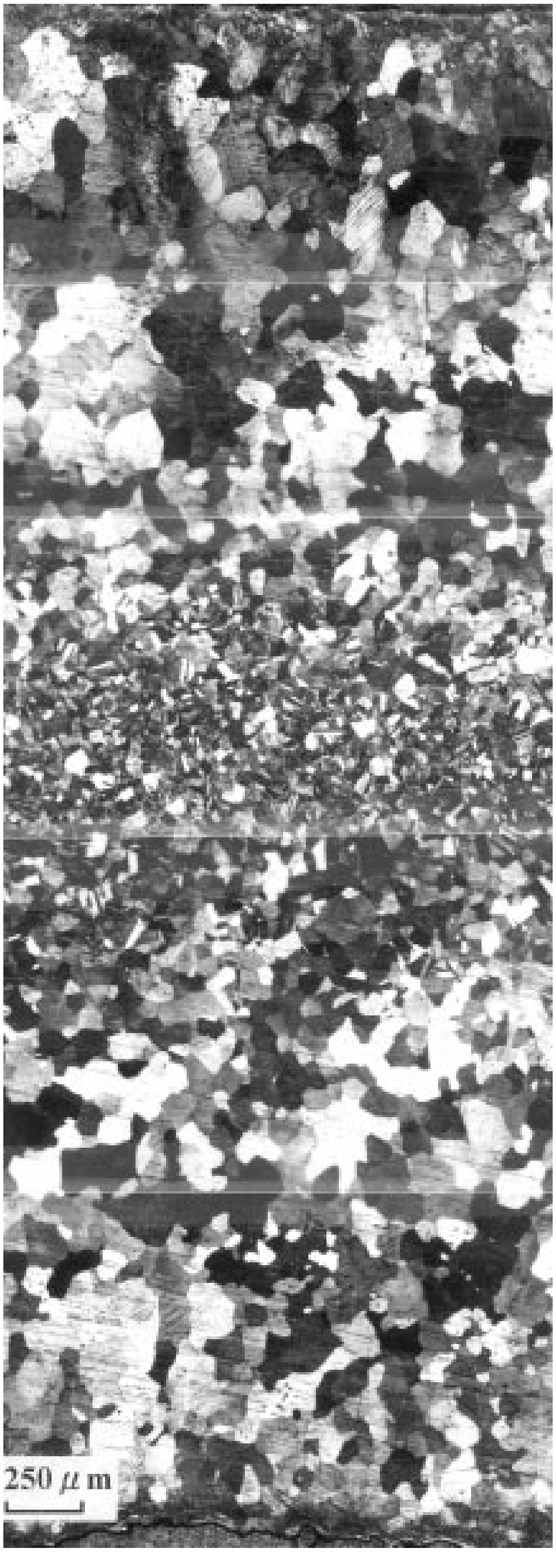


Fig. 3 Microstructure (grain structure) of as-cast phosphor bronze strip produced by the twin roll caster with the following casting conditions: setback = 80 mm, casting speed = 15 m/min, roll gap = 4.5 mm, roll separating force = 1 ton, and pouring temperature = 1065 °C

Figure 4 shows the transverse cross section solidification structure of plate B cast by the HCC process (15.6 mm thick by 480 mm wide) with a casting speed of 0.2 m/min. In this figure, a narrow zone of tiny grains near the surface and a columnar zone occupying the rest of the area are visible. The chill zone with tiny grains is caused by chilling of the graphite mold. The coarse columnar grains grow directionally from the chill zone toward the central part of the cast plate with a relatively slow casting speed. The average size of the coarse columnar grains is about 1 to 2 mm, which is much larger than those in plate A.

The dendrite structures of both plate A and plate B are illustrated in Fig. 5. The orientation of the dendrite structure appearing in plate A is randomly distributed, as shown in Fig. 5(a). The measured secondary dendrite arm spacing within 1 mm from the surface varies from 7 to 9 μm. According to the derivation by Essadiq (Ref 11), the relationship between the cooling rate (R in °C/s) and secondary dendrite arm spacing (λ in μm) can be represented by the following:

$$\lambda = 101 \cdot R^{-0.42} \quad \text{(Eq 1)}$$

Consequently, the average cooling rate of twin roll cast C5191 alloy (plate A)is estimated to be 475 °C/sec. Figure 5(b) shows that the dendrite structures of plate B are all aligned directionally toward the center of the casting. The measured secondary dendrite arm spacing (2 to 3 mm from the surface) is around 16 to 18 μm, and hence, the calculated cooling rate estimated by Eq 1 is approximately 68 °C/s, which is much slower than that used for plate A.

Fig. 4 Microstructure (grain structure) of as-cast phosphor bronze plate produced by the HCC process (plate width = 480 mm, plate thickness = 15.6 mm, and casting speed = 0.2 m/min)

3.2 Analysis of Macrosegregation

The contents and distributions of tin (Sn) in plate A and plate B are obtained from ICP-AES analysis of chips removed from the castings. Figure 6(a) illustrates the variations in tin content with respect to the distance from surface to the center of plate A produced by the twin roll caster. No apparent inverse segregation is visible in the surface region. This may be due to the very short contact time ($t_c = 0.32$ s) associated with the rapid casting speed and the high cooling rate (475 °C/s) used during the casting process. Therefore, negative pressure and the capillary force between the roll and the strip would not develop to induce the solute-rich melt to backflow. Additionally, a slightly higher tin content in the central region is observed, which may cause some constitutional supercooling in the central region where the melt solidifies last. However, the increase in tin is not significant, as shown in Fig. 6(a). This seems to suggest that some other mechanism such as recrystallization caused by the deformation strain from the caster and the high temperature in central region during casting may also contribute to the formation of fine grains.

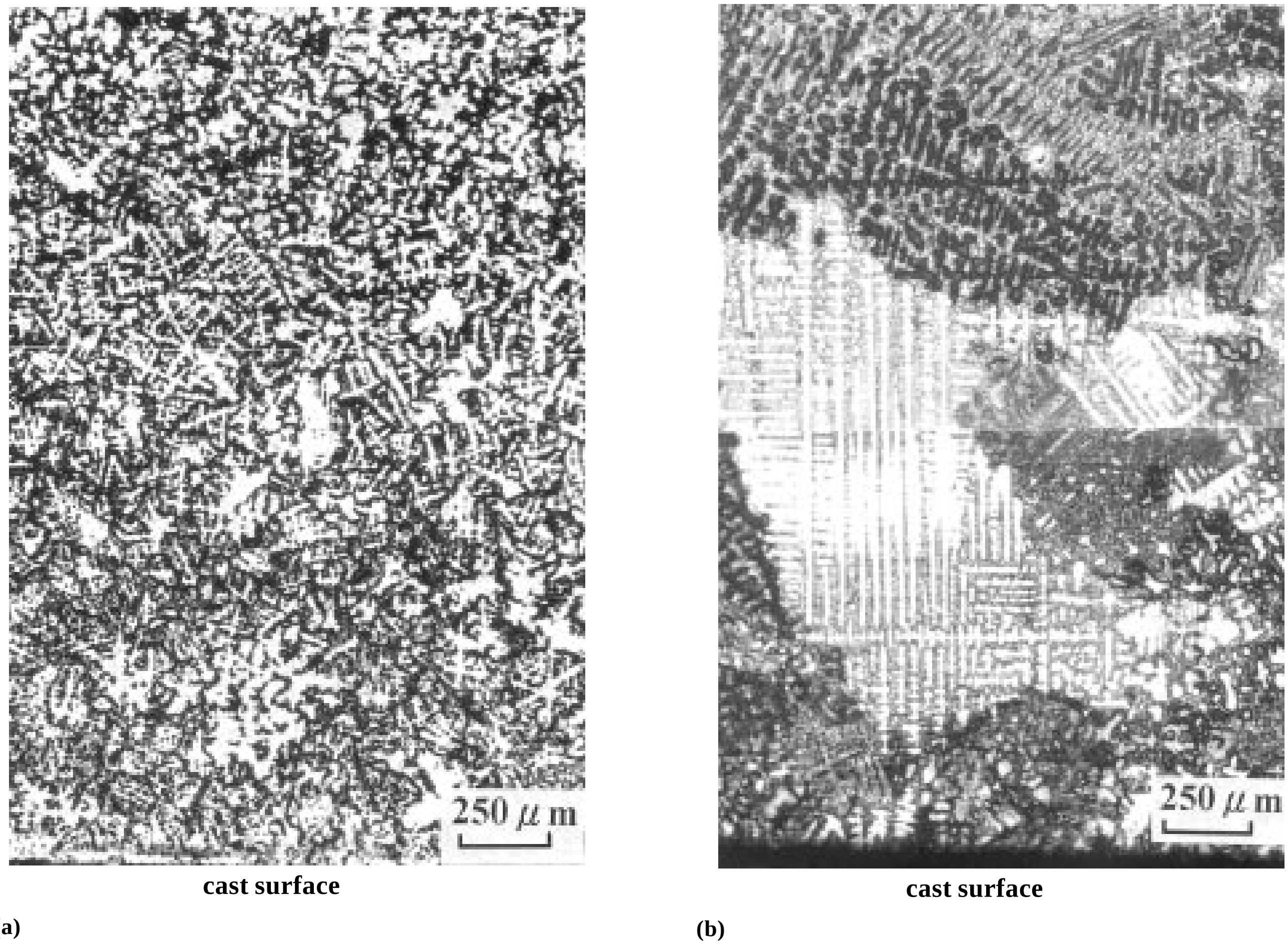
Figure 6(b) shows the variations in tin content with respect to the distance from the surface to the central region of plate B (produced by the HCC process). Inverse segregation is clearly visible within the 1-mm region near the surface due to the negative pressure built up between the graphite mold and the casting. As a result, the solute-rich and low-melting-temperature liquid phase in the central region moves through the interdendritic spacing to the casting surface, thus forming a solute-rich (Sn, P) layer near the surface. This solute-rich layer must be milled away before further cold rolling, otherwise hot tearing or cracking may occur. In commercial production, a surface layer of 0.5 to 1 mm thick usually is removed from both the cast surfaces of a phosphor bronze plate produced by the HCC process to alleviate the problems of inverse segregation and microporosity.

3.3 X-Ray Diffraction (XRD) Results

Figure 7 shows the x-ray diffraction patterns of plate A and plate B produced by the twin roll strip casting and the HCC process, respectively. From these XRD patterns, only α phase can be found, with no evidence of other second phases such as ε and Cu_3P present. However, there is a significant difference associated with the preferential orientation between these plates. The HCC plate (plate B) exhibits a strong {220}//ND preferred orientation, as shown in Fig. 7(b), whereas the XRD pattern (Fig. 7a) of the twin roll cast strip (plate A) does not. This observation of strong preferential orientation correlates well with the columnar structure shown in Fig. 4 and the aligned dendrite structure in Fig. 5(b). However, the observed texture of the as-cast material has no effects on the final products after subsequent cold rolling and annealing treatments. This is discussed further in the following section.

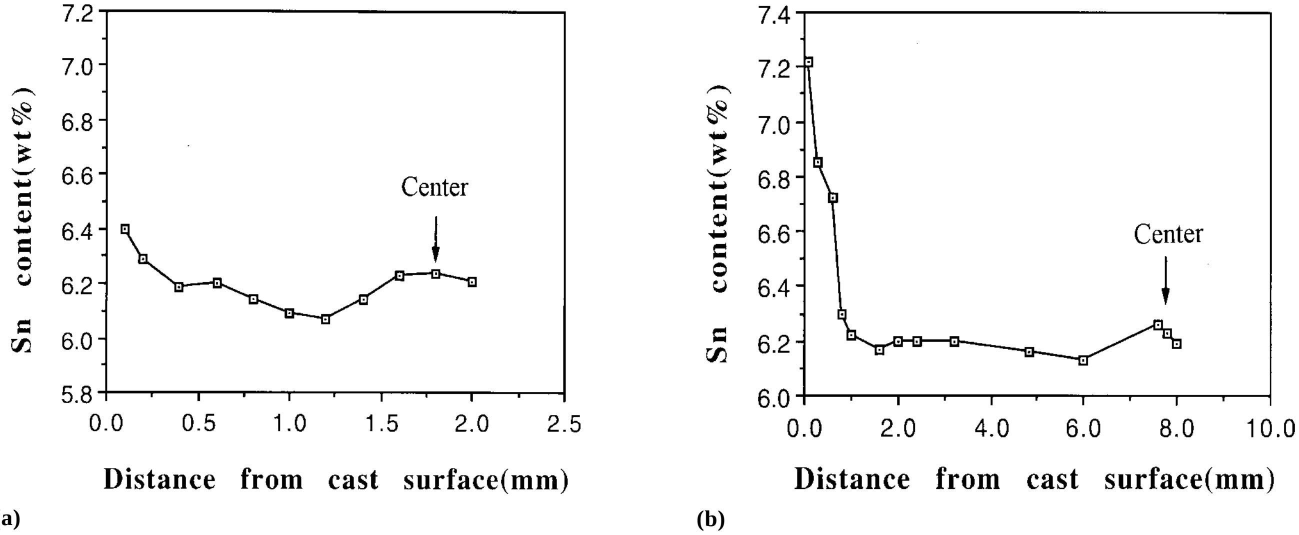
3.4 *Microstructures and Mechanical Properties of Rolled Sheet*

The initial thickness (d_o = 4.5 mm) of twin roll cast plate was cold reduced to a final thickness (d_f) of 0.3 mm via four stages of cold rolling and interstage annealing treatments, as indicated in Fig. 2. The change in thickness corresponds to a logarithmic strain ψ ($\psi = \ln(d_o/d_f)$) of 2.7 or 15-fold reduction. Figure 8 shows the microstructure of sheet after the second



(a) (b)

Fig. 5 Dendritic structures of the phosphor bronze strip/plate cast by (a) twin roll casting and (b) the HCC process



(a) (b)

Fig. 6 Distribution of tin content through half of the strip/plate thickness cast by (a) twin roll casting and (b) the HCC process stage rolling procedure with a subsequent annealing at 550 °C for 1 h. Many equiaxial recrystallized grains and intragranular annealing twins are visible. The distribution of grain sizes across the thickness direction as shown in Fig. 8 is much more uniform compared to that of the as-cast plate in Fig. 3. The as-rolled microstructures of the end products (JIS H grade) obtained from both processes are shown in Fig. 9. Numerous elongated grains are visible along the rolling direction. The as-rolled microstructures of the end products of these two processes look similar, despite the fact that the starting materials experienced appreciably different amounts of deformation.

Tensile tests were made for specimens taken from locations on the edge, 1/4 width, and central regions of the final sheet produced by the strip casting process. Likewise, these tests also were performed on the HCC processed sheet. Test results indicate there is no marked difference in mechanical properties of specimens taken from the twin roll processed sheet, as indicated in Table 3. This observation suggests that subsequent thermal mechanical treatments after casting have homogenized the microstructures and hence the resultant mechanical properties in various locations as well. Moreover, the mechanical properties of the sheet obtained from the two casting processes are comparable to each other, and both meet the specifications of JIS H3110 for the commercial phosphor bronze sheet of H grade. However, it is important to note that the material obtained from the twin roll caster has experienced a significantly less logarithmic strain (ψ = 2.7, or 15-fold reduction) than the HCC processed material (ψ = 4.0, or 54.4-fold reduction). This leads one to believe that the twin roll cast strip with its finer equiaxed grains requires only minimal subsequent deformation to generate mechanical properties comparable to those of conventionally processed sheet.

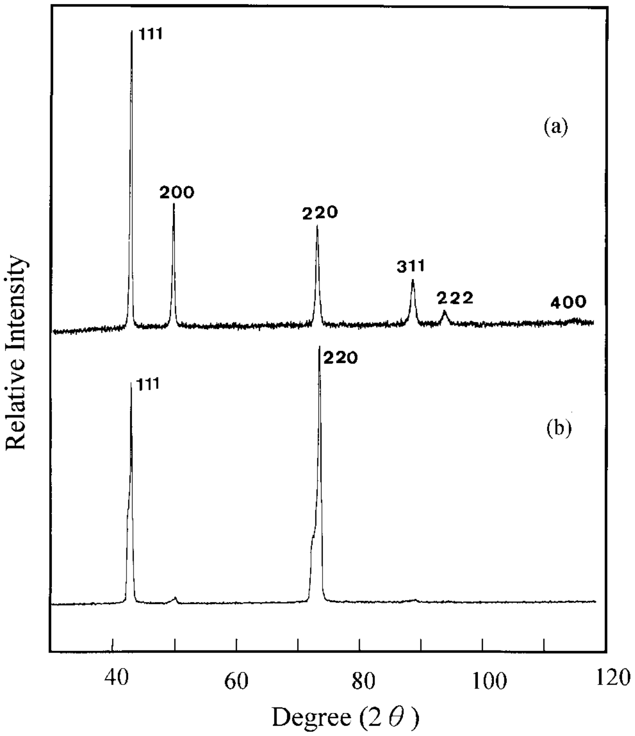


Fig. 7 X-ray diffraction patterns of as-cast phosphor bronze strip/plate produced by (a) twin roll casting and (b) the HCC process

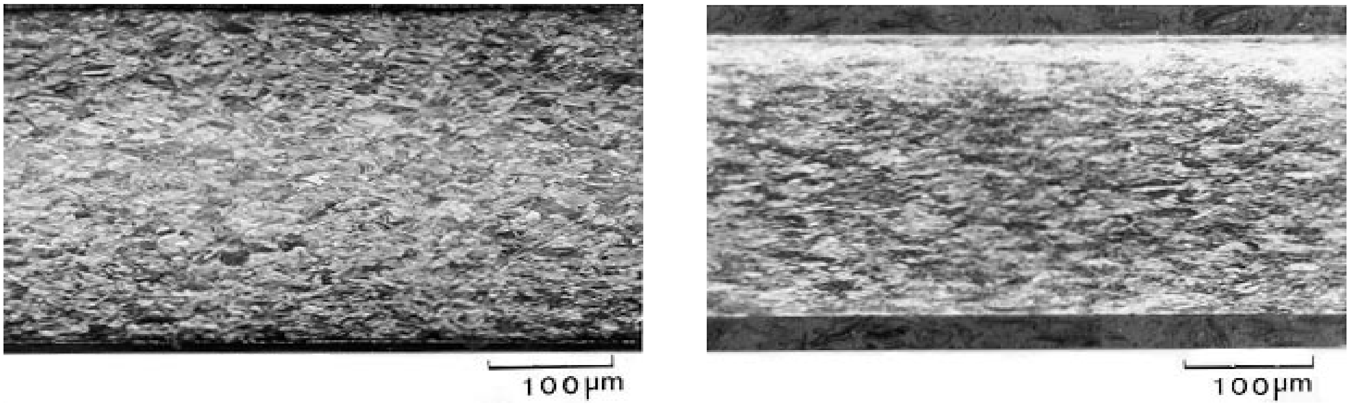
3.5 Texture

To further investigate the problem of preferential orientation in as-cast materials obtained from twin roll casting and HCC processes, x-ray pole figure examinations were also conducted. Figure 10(a) and (b) illustrate the (111) pole figures of the materials obtained from the twin roll strip casting and HCC

Fig. 8 Microstructure of as-annealed phosphor bronze sheet produced by twin roll casting after cold rolling and annealing at 550 °C for 1 h

processes, respectively. No casting texture is visible in the material produced by the twin roll caster, as shown in Fig. 10(a). This corresponds to the equiaxial grains and randomly distributed dendrite structures shown in Fig. 3 and Fig. 5(a). Conversely, the casting texture is visible in the material produced by the HCC process, as shown in Fig. 10(b). This observation is consistent with the x-ray diffraction pattern shown in Fig. 7(b). However, the contours of pole figure in Fig. 10(b) are discontinuous, and it is difficult to identify the orientations of the casting textures due to the larger grain sizes (1 to 2 mm) in the HCC plate.

Figures 11(a) and (b) show the (111) pole figures of the sheet obtained from the two processes, respectively. Both of the deformation textures obtained after thermal mechanical treatments appear similar, and they contain predominantly the orientations of {110} <112>, {123} <412>, and {416} <211>. This as-rolled “brass-type” deformation texture of phosphor bronze sheet is consistent with those reported in the literature (Ref 16, 17). It was therefore concluded in this study that the casting texture had no apparent effect on the deformation texture after a series of cold rolling and annealing treatments.



(a) (b)

Fig. 9 Microstructures of as-rolled phosphor bronze sheet of the final products (H grade) obtained by (a) twin roll casting and (b) the HCC process

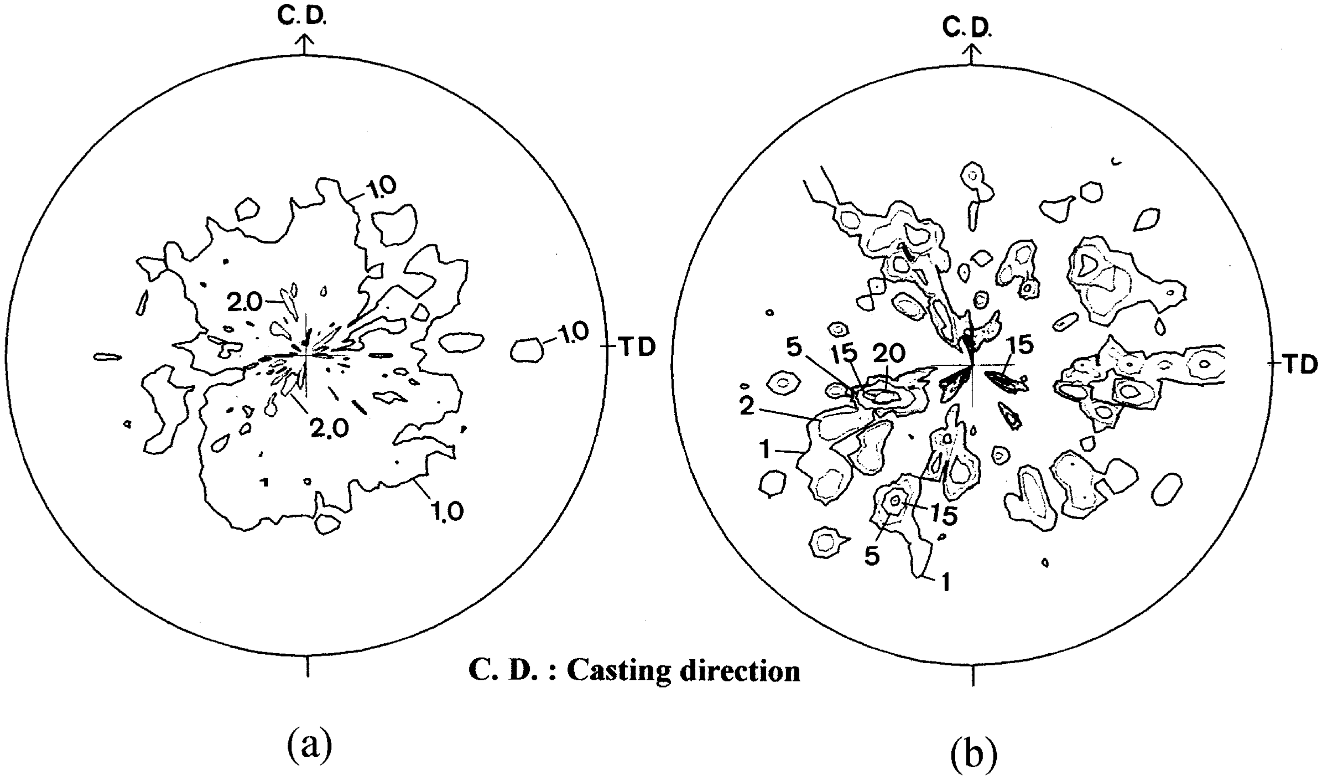
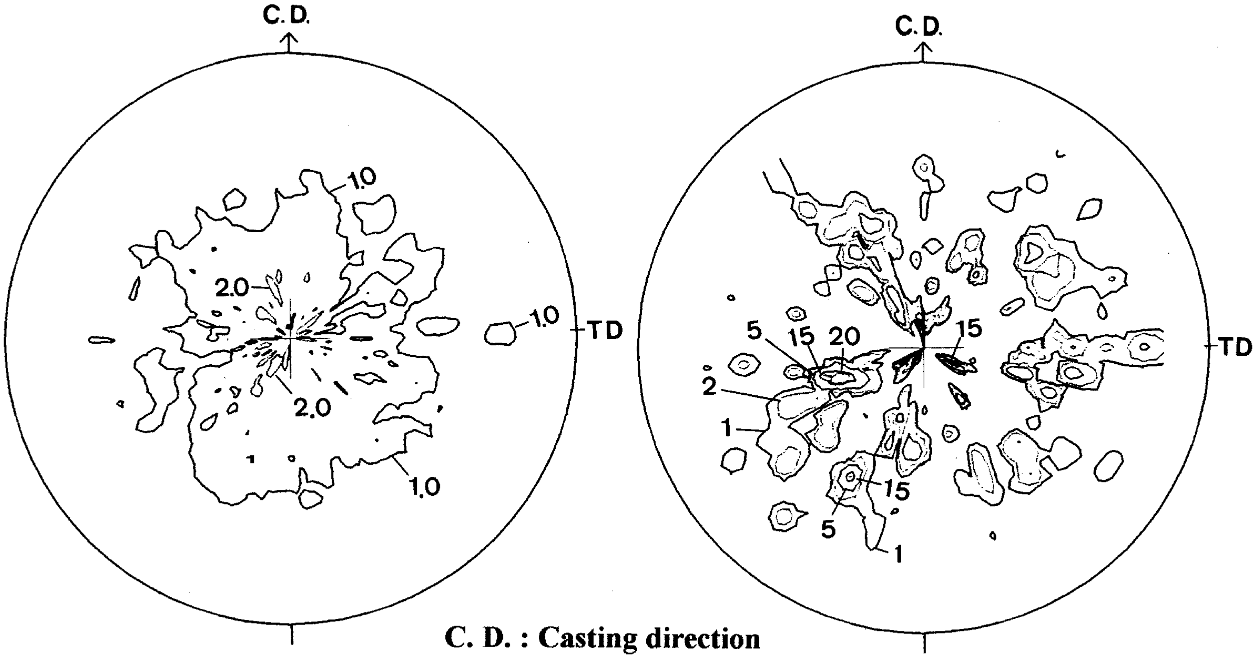


Fig. 10 (111) pole figures of as-cast phosphor bronze strip/plate produced by (a) twin roll casting and (b) the HCC process



(a)

(b)

Fig. 11 (111) pole figures of the final phosphor bronze sheet (H grade) obtained by (a) twin roll casting and (b) the HCC process

Table 3 Mechanical properties of phosphor bronze sheet (H grade)

Process	Thickness, mm	Position	Tensile strength, kg/mm^2	Elongation, %	Hardness, HV
Twin roll	0.30	L-edge	60.3	12.17	…
casting process		L-1/4w	59.6	11.7	187 ± 4
		L-center	58.7	11.1	…
HCC process	0.25	L	63.3 (avg)	11.4 (avg)	194 ± 3
JIS H3110	0.2 to 0.5	L	56 to 68	>8	180 to 230

Note: L, longitudinal direction. W, strip width

4. Conclusions

The present study demonstrates the technical advantages of a new fabrication process—the twin roll strip casting—for producing the phosphor bronze (C5191) alloy. Some important results are summarized below.

The mechanical properties of the sheet obtained from the twin roll casting method and the HCC method are comparable to each other, and both meet the requirements of JIS H3110 and ASTM B 103M specifications for the H grade phosphor bronze sheet.

No inverse segregation is visible in the twin roll cast strip. This can be attributed to the rapid casting speed and the high cooling rate obtainable in this process. However, inverse segregation was clearly visible within 1 mm of the surface region of the cast plate produced by the HCC process.

The evidence presented suggests that solute enrichment of tin in the central region of the twin roll cast strip is responsible for the formation of fine equiaxed grains. However, it can be postulated that the recrystallization process induced by hot deformation during casting might also generate the fine equiaxed grains.

The bi-mode distribution (inner fine equiaxed zone and outer coarse equiaxed zones) of the solidification structure of the twin roll cast plate can be eliminated by subsequent thermal mechanical treatments. Mechanical properties corresponding to various locations on the final sheet are relatively uniform.

A significant difference exists between the two processes in terms of preferred orientation in the as-cast condition. However, subsequent thermal mechanical treatment can eliminate the difference in texture (preferred orientation).

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