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Some Perspectives on Innovative Processing and Materials Development

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Throughout a long and distinguished career, the research activities conducted by Professor Ravindran have been characterized by the quest to generate fundamental as well as practical knowledge through collaborative efforts involving academia and industry as a basis for development of innovative manufacturing routes and improvement in performance of existing products and processes based on near-net-shape casting technologies. In this paper, the generation, validation, and implementation of new knowledge is illustrated by the Ohno Continuous Casting process, a heated mold system that permits the production of net-shape or near-net-shape products with a high-quality surface, controlled solidification structure, and significantly enhanced properties.

Keywords cast wire, continuous casting, directional solidification, heated mold, single crystal

1. Cast Structure Control

One of the important factors that influence the properties of cast products is cast structure (Ref 1). Therefore, control of cast structure is vitally important for enhancing the mechanical integrity of cast products. In order to do so, it is essential to understand how cast structure forms during solidification. Formation of the fine copious equiaxed grains that occur along the outer surface of castings was believed to be generated due to local supercooling near the chill wall. However, it was subsequently discovered that local supercooling alone does not cause the chill zone and the presence of convection in the melt is an essential element for crystal multiplication, and thus it was concluded that some forms of crystal multiplication play an important role in the formation of the chill zone (Ref 2).

It was also found that these crystal multiplication mechanisms play a significant role in the formation of equiaxed grains observed in the interior parts of ingots (Ref 3-5). Solidification experiments were carried out in the late 1960s involving the vibration of the molten metal surface in the initial stage of solidification. Aluminum alloys containing a small amount of copper, titanium, or beryllium were melted in clay-graphite crucibles, the outer surface of which, as shown in Fig. 1, was totally or partly coated with vitrified water glass, and dipped in water almost to the rim. The resulting solidification structures were observed. As shown in Fig. 2(a), the cast structure produced using an entirely coated crucible contained only coarse-elongated columnar grains growing from the outer edge of the ingot toward the shrinkage pipe. When another crucible, the top part of which was left uncoated, was used, Fig. 1(b), the melt surface produced minute vibrations near the crucible edge at the initial stage of solidification due to the moisture seeping through the crucible wall. The resultant solidification structure, as shown in Fig. 2(b), contained an equiaxed zone in a U-shaped formation, as if these equiaxed grains fell from the upper region of the ingot. When a stainless-steel net was placed horizontally within the middle of the melt, Fig. 1(c), before dipping the crucible into water, the equiaxed grains accumulated only above the net. Under the net, there were only large columnar grains, Fig. 2(c), clearly implying that the fine grains were not generated by constitutional undercooling, but were separated from the crucible wall at the initial stage of solidification due to vibrations. When there was no vibration at the interface, no such fine equiaxed grains were observed, Fig. 2(a).

Figure 3 shows the results for the Al-Be alloy that exhibited the largest areas with fine equiaxed crystals. At first glance, it is hard to imagine that all of these fine crystals were formed at the initial stage of solidification in the upper region of the crucible wall where minute vibrations occurred. However, when a stainless-steel net was placed horizontally within the melt, fine equiaxed crystals existed only above the net, indicating that these fine crystals formed on the crucible wall and then separated. All three alloys exhibited similar results with the only difference being the amount of equiaxed crystals.

2. Direct Observation of the Solidification Process

In order to further clarify how and when these equiaxed crystals formed, the solidification phenomena for Sn-Bi alloys

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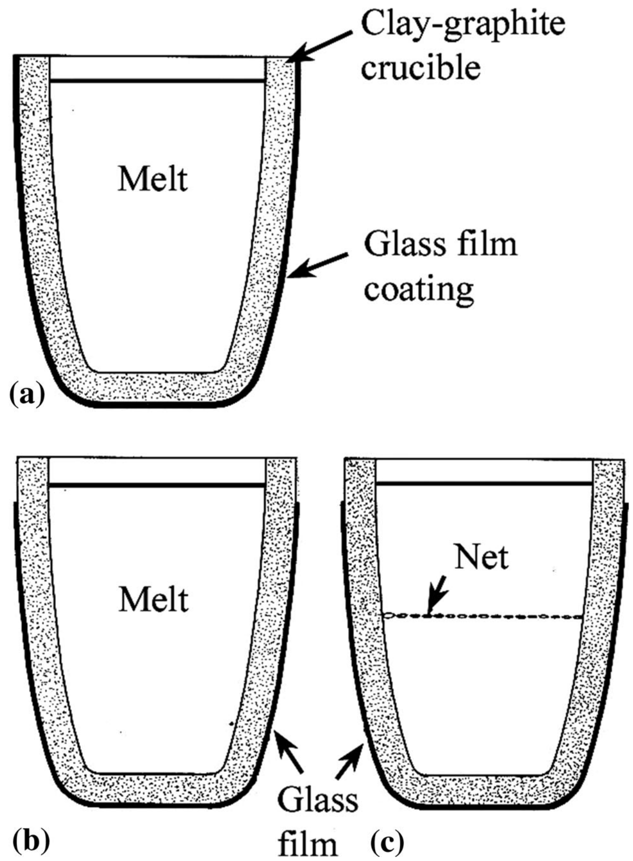

Fig. 1 Schematics of clay-graphite crucibles with a glass-film coating of sodium silicate on the outer surface; (a) coated entirely, (b) upper part was not coated, and (c) upper part was also not coated and a stainless-steel net was placed horizontally within the melt (Ref 3)

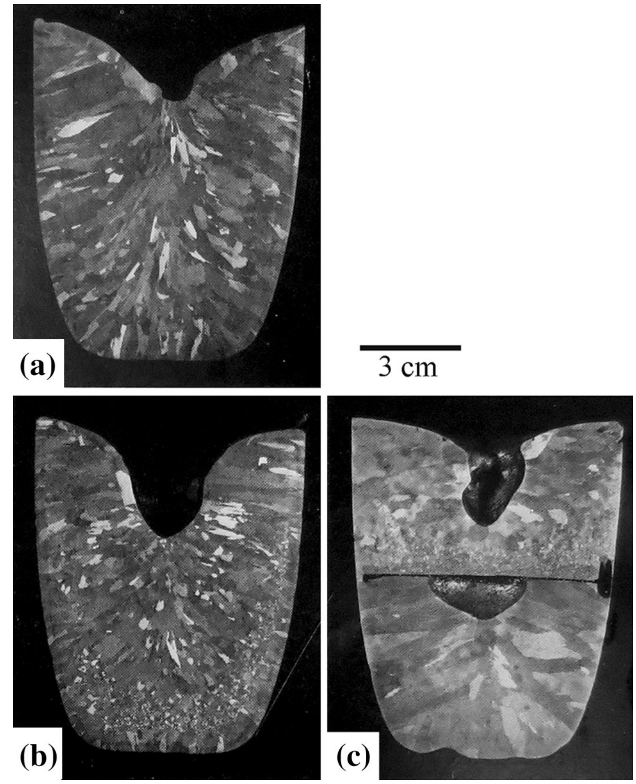

Fig. 2 Solidification structure of Al-0.2%Cu alloy; (a) solidified in a crucible, shown in Fig. 1(a), (b) solidified in a crucible shown in Fig. 1(b), and (c) solidified in a crucible shown in Fig. 1(c) (Ref 3, 4)

were directly observed using the setup shown in Fig. 4 (Ref 6). It was observed (as indicated by arrows in Fig. 5) that the crystals were formed on the air-cooled glass wall (dark areas) and grew in globular shapes which detached from the wall and moved to the hotter end of the glass tube due to the convection occurring within the melt, a cycle which occurred repeatedly. The observations clearly show that copious amounts of crystals can form on the cooled wall at the initial stage of solidification. It also shows that globular-shaped crystals on the wall can easily be separated solely by convection occurring in the melt without any other external forces such as vibration.

3. Development of the OCC Process

The fundamental studies on solidification structure described above led to the concept of the Ohno Continuous Casting (OCC) process (Ref 7-9) in the mid-1980s at the Chiba Institute of Technology in Japan. Professor Ohno conducted his Doctoral Studies in the early 1960s at the University of Toronto. In 1988, the Ohno Continuous Casting Laboratory was established at the University. Unlike conventional continuous casting which uses a water-cooled mold, the OCC process involves a heated mold technique, as illustrated schematically in Fig. 6 (Ref 9). With the OCC process, molten metal is introduced continuously into an externally heated mold, the temperature of which is held just above the solidification temperature of the metal to be cast, thus preventing the nucleation of crystals on the mold surface. Heat is extracted from the cast product by means of cooling water located near the mold exit, differentiating the direction of heat flow in the OCC process from that in the traditional continuous casting process. This makes it possible to obtain unique solidification structures with associated characteristic properties. The OCC principle can be utilized for either vertical or horizontal casting. Figure 7 shows a schematic diagram of the horizontal OCC system which consists of a melting furnace, a cylindrical displacer block for molten metal level control, a heated graphite mold, a water-cooling device, and pinch rolls for withdrawal of the cast product (Ref 9). The photograph included in Fig. 7 shows a close-up view of a single-crystal copper wire being produced (Ref 10).

Since the inception of the process, numerous research studies have been conducted pertaining to the fundamental aspects as well as their practical implications. These developmental efforts have taken place through laboratory experiments, pilot plant trials, and university-industry collaborations. The process has been implemented in regular production by companies in Japan, Taiwan, China, and Canada as a method of generating unique net-shape or near-net-shape cast products. The characteristic features of the process include the ability to produce.

- single-crystal or unidirectionally cast products (Ref 7, 8, 10-13);
- net or near-net-shape cast products (Ref 9, 13-16);

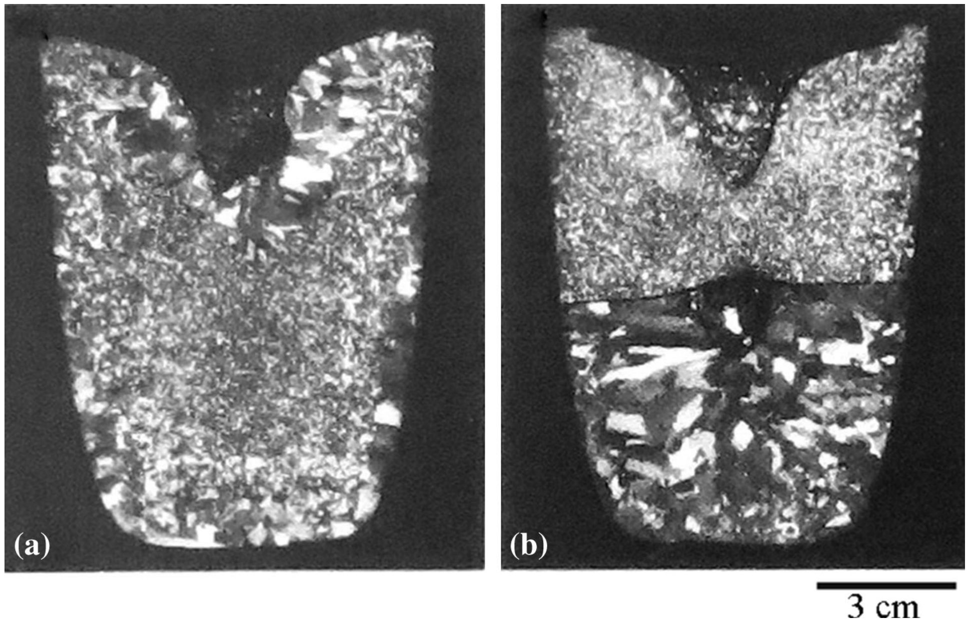

Fig. 3 Water-cooled solidification structure of Al-0.3%Be alloy; (a) solidified in a crucible schematically shown in Fig. 1(b), and (b) solidified in a crucible shown in Fig. 1(c) (Ref 3)

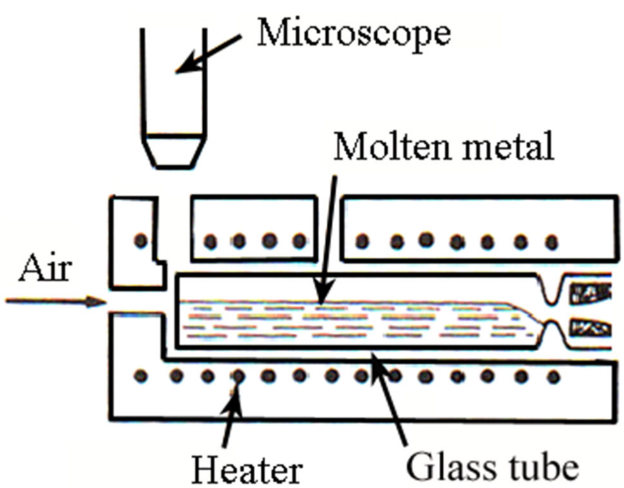

Fig. 4 Setup for in situ observations of crystal formation and separation during solidification of tin-bismuth alloys (Ref 6)

- a clean, mirror-finish surface with no witness marks (Ref 8, 17);
- cast products with fewer cavities and porosity defects (Ref 17);
- cast products with a fine uniform crystal structure (Ref 16, 18-20); and
- cast products with good ductility (Ref 18, 21-25).

4. Some Examples of OCC Products

Figure 8(a) to (d) shows various microstructures of the 77 °C-Bi-In-Sn eutectic alloy: (a) solidified by furnace cooling showing gravity-induced segregation of brittle bismuth phases (white); (b) slow directional growth showing the segregation of complex bismuth structures (white) along the grain boundaries; (c) quick cooling by suctioning the melt into a small glass tube of 2 mm inside diameter, showing non-uniform structure; while in (d) the microstructure obtained by the OCC process was finer and much more uniform with the discrete bismuth phase (white) dispersed in the matrix phase (Ref 19). These differences in the microstructure generated by OCC exerted a significant influence on ductility as shown in Fig. 9.

Since heat flow is unidirectional, single-crystal, or unidirectionally structured materials can be cast continuously within a specific window of processing parameters with superb surface finish (Ref 7, 8, 10, 12, 26). As shown in Fig. 10, casting of single-crystal copper wires of 4 mm in diameter containing fewer subgrain boundaries can be generated with casting speeds under approximately 50 mm/min (Ref 10). These features led to the early commercial implementation of the OCC process for the production of specialized high-purity copper and silver rods and wires for the audio and video cable industries (Ref 27, 28). With the OCC system, solidification occurs along the casting direction at or near the mold exit (Fig. 6 and 7). As a result, mold-strand friction is greatly reduced or entirely eliminated, permitting the generation of a wide range of products with small-diameter and superb cast surfaces as shown in Fig. 11.

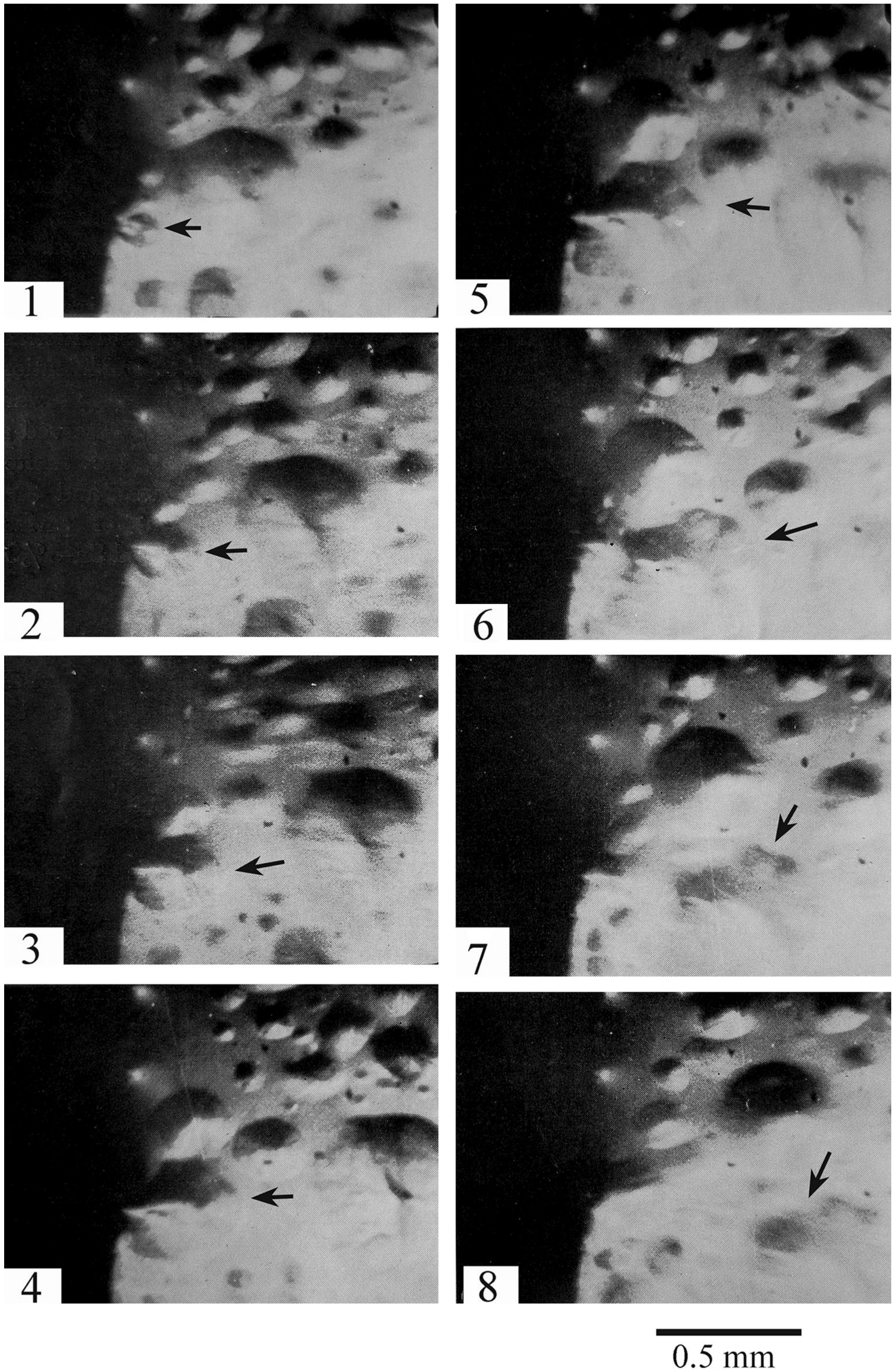

Fig. 5 Formation, growth, and separation of crystals, indicated by arrows, during the initial stage of solidification of a Sn-10%Bi alloy (Ref 6). The dark area on the left is the glass wall

This net-shape casting capability of the process led to the development of cast aluminum welding rods containing 25-45%Cu alloy for hard-facing applications (Ref 29) and aluminum rare-earth alloy wires (Al-Y, Al-Ce, Al-La) of 1.8 mm in diameter for vapor deposition applications to produce oxidation-resistant coatings (Ref 13, 30, 31). Other

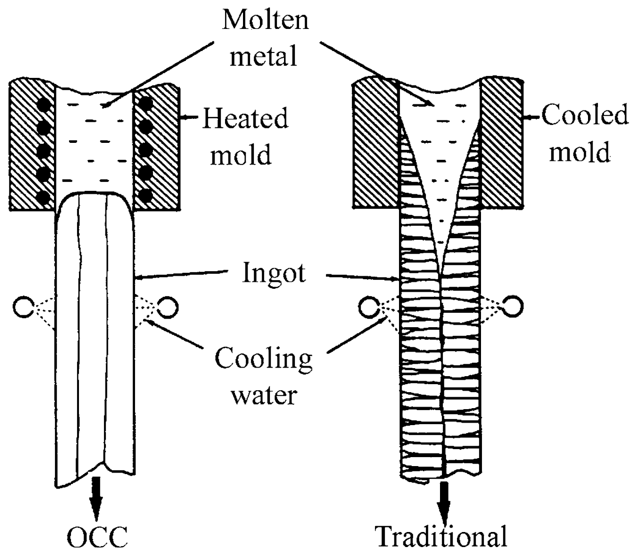

Fig. 6 Schematic diagram of the Ohno Continuous Casting (OCC) process in contrast to a traditional continuous casting process (Ref 9)

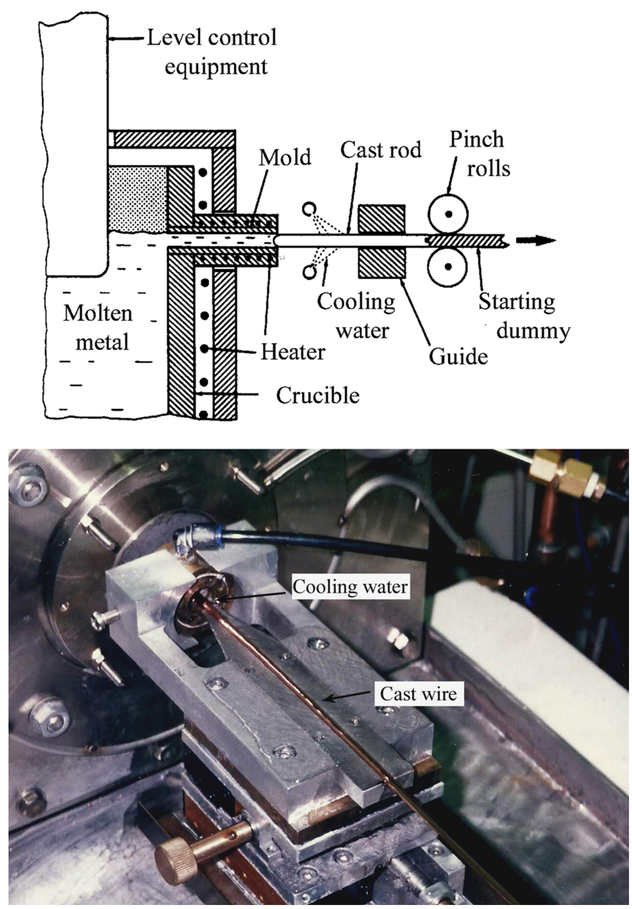

Fig. 7 Schematic diagram of horizontal OCC system (Ref 9) and casting of single-crystal copper wire of 4 mm in diameter (Ref 10)

examples of the net-shape capability of the process are copper and stellite alloy tubes and rods with complex cross-sectional geometries, shown in Fig. 12 (Ref 14).

With the OCC process, the presence of free-growing crystals in the liquid ahead of the solidification front is avoided due to the externally heated mold. This eliminates the possibility of solid phases segregating due to gravity. Moreover, as opposed to conventionally produced cast products in which the solidification fronts meet at the center line resulting in solute segregation and shrinkage cavities (Fig. 13), the OCC process can generate products which are free from centerline defects. These high-quality products generated by the OCC process are being used within the dental community as shown in Fig. 14. Co-Cr-Mo-based alloys are cast into rods of 7 mm in diameter by the OCC process in order to produce high-quality cylinders as implant materials (Fig. 15).

5. Closing Comment

Throughout his long and distinguished career within industry and at Ryerson University, the activities of Professor Ravindran have provided firm foundations for progress within the areas of metallurgical processing and materials development. His pronounced influence for good on the education and training of numerous of young engineers has been outstanding. In all of our efforts aimed at innovative processing, an activity that encompasses generation, validation, and application of knowledge; quality communications; university-industry collaborations; and the training of people, let us resolve to emulate the highest standards of achievement and professionalism so well exemplified by our distinguished colleague and honored friend, Professor Ravindran.

6. Summary

Based on findings from studies carried out on the solidification structures and the origins of equiaxed crystals in cast products, a groundbreaking processing system, known as OCC, has been developed with the aid of collaborative projects between academia and industry. Using a heated mold concept, fundamental and practical studies have been undertaken within the laboratory, validated in pilot plant trials, and implemented in production operations. These collaborative efforts have led to new processing routes for the generation of net or near-net-shape products such as small-diameter rods, tubes, wires, and cored materials suitable for niche markets that include audio cables, dental implants, and thermal fuse wire applications (Ref 32).

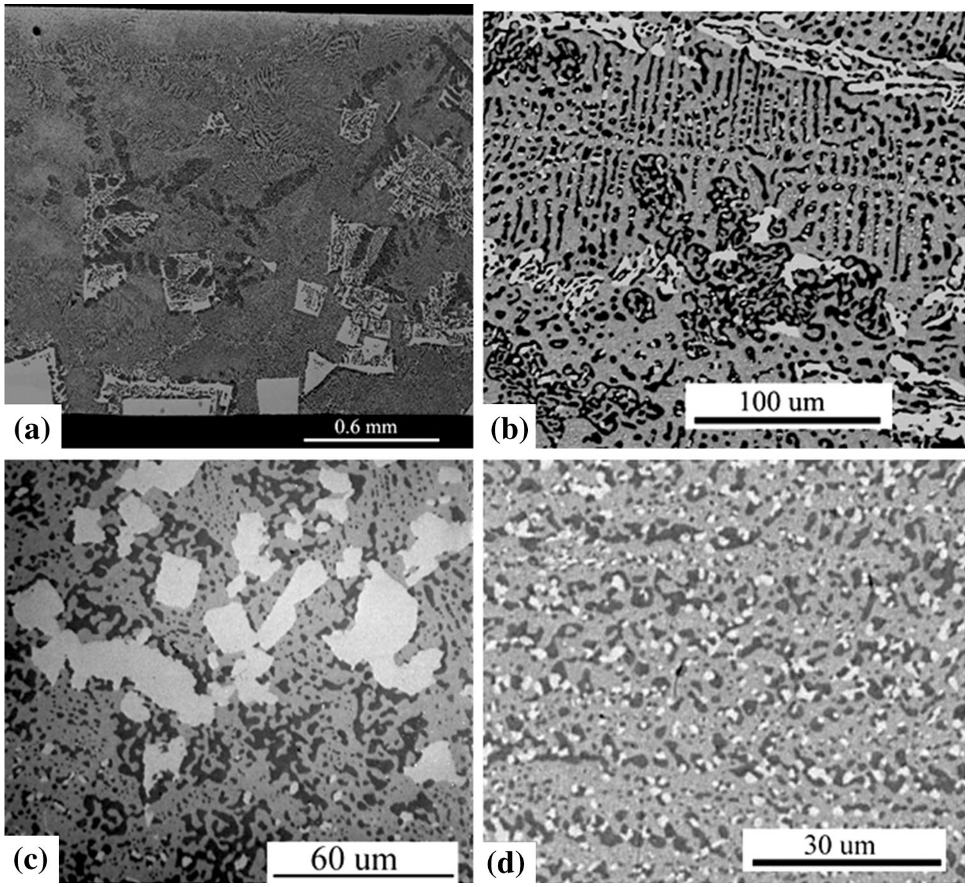

Fig. 8 Various microstructures of the 77 °C-Bi-In-Sn eutectic alloy; (a) solidified within the furnace at a cooling rate of 1 °C/min, (b) solidified unidirectionally at a speed of approximately 2 mm/min, (c) solidified by suctioning the melt into a glass tube, and (d) generated by OCC (Ref 19)

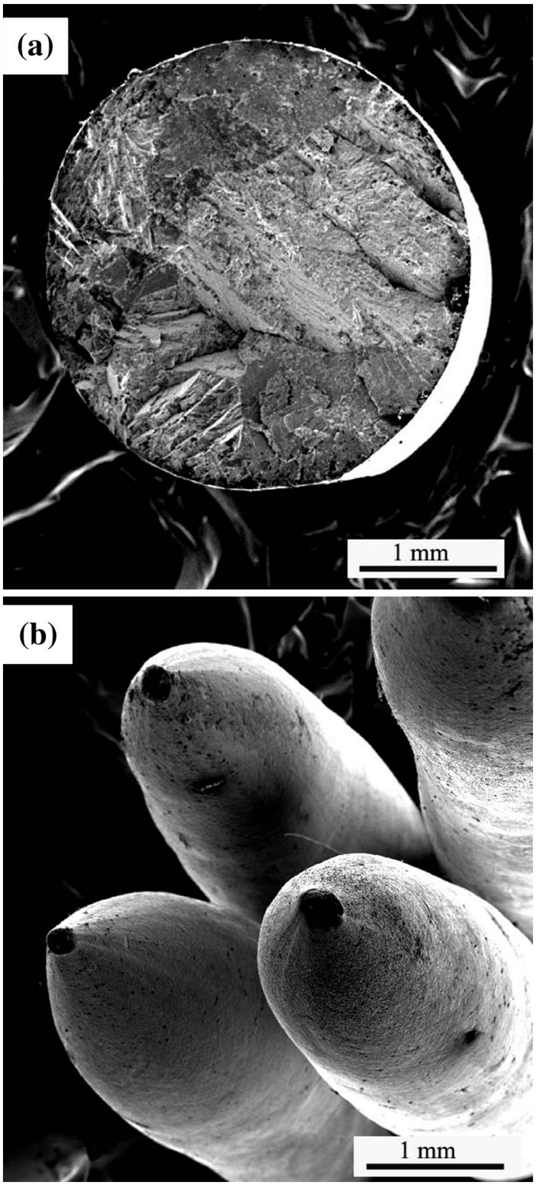

Fig. 9 Differences in ductility of the Bi-In-Sn eutectic alloy specimens; produced by (a) furnace cooling and (b) OCC process. The initial strain rate was 6.67×10^{-3}/s (Ref 25)

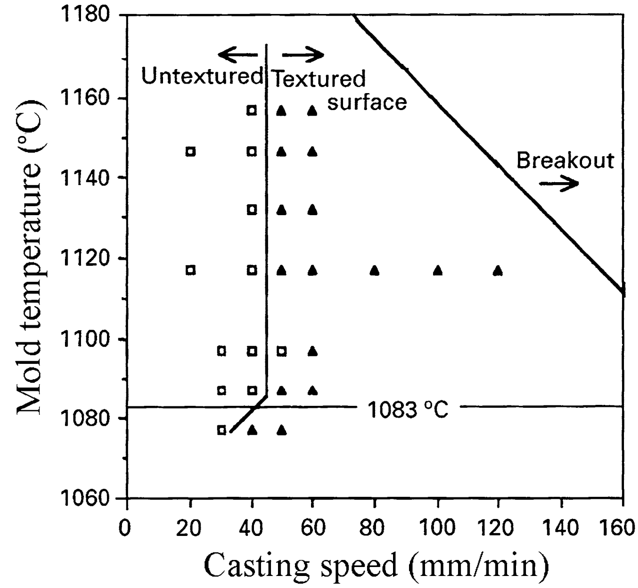

Fig. 10 Casting regime diagram for single-crystal copper wires of 4 mm diameter with no visible surface texture (Ref 10)

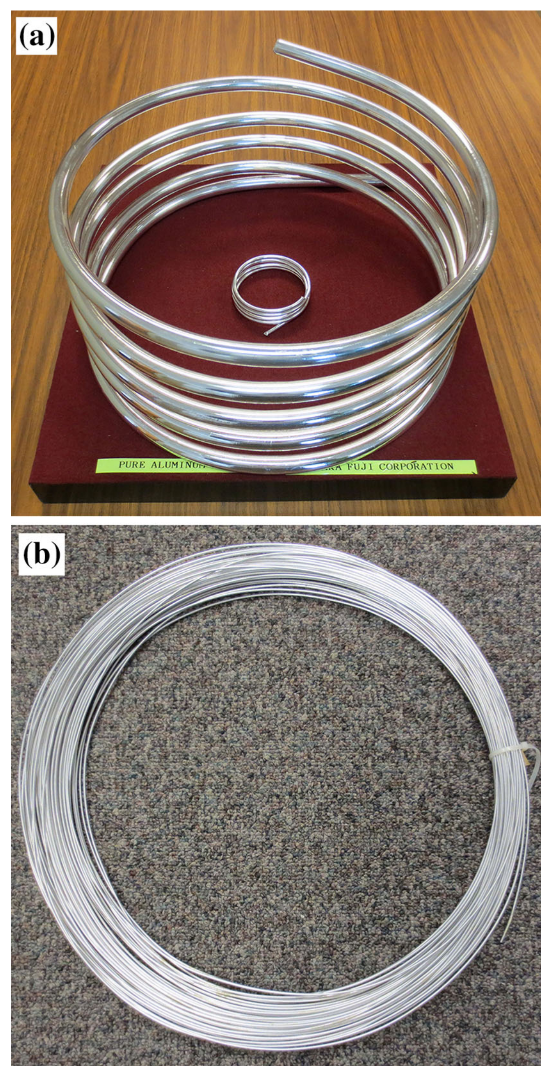

Fig. 11 (a) As-cast pure aluminum wires of 4 mm and 15 mm in diameter, showing a mirror surface (Osaka Fuji Corp. Japan) and (b) as-cast Al-2.8%Ce wire of 1.8 mm diameter and approximately 70 m long for vapor coating of turbine blades

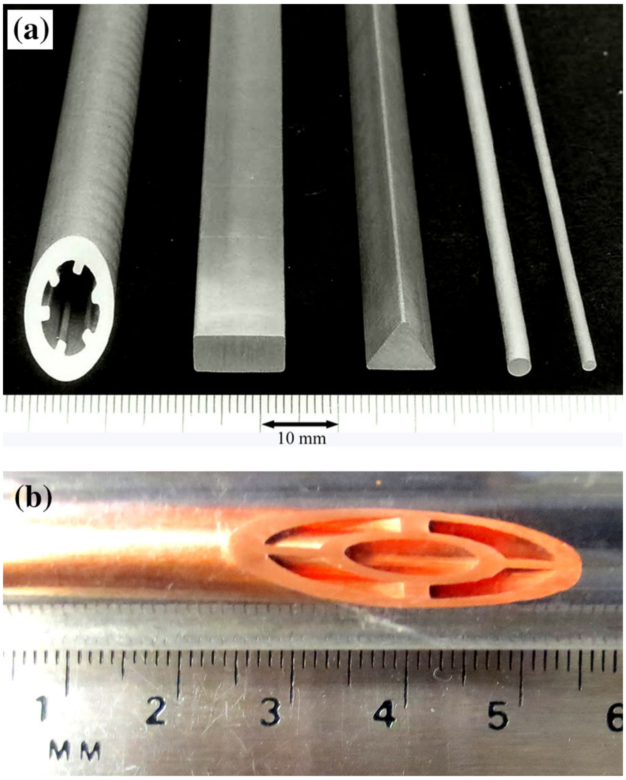

Fig. 12 Examples of net-shape cast products; (a) as-cast stellite tube and rods of different cross-sectional shapes (Co-30%Cr-12%W-2.5%C-<3%Fe) (Osaka Fuji Corp. Japan) and (b) as-cast copper tube (Mitsui Shipbuilding Co, Japan) (Ref 14, 15, 17)

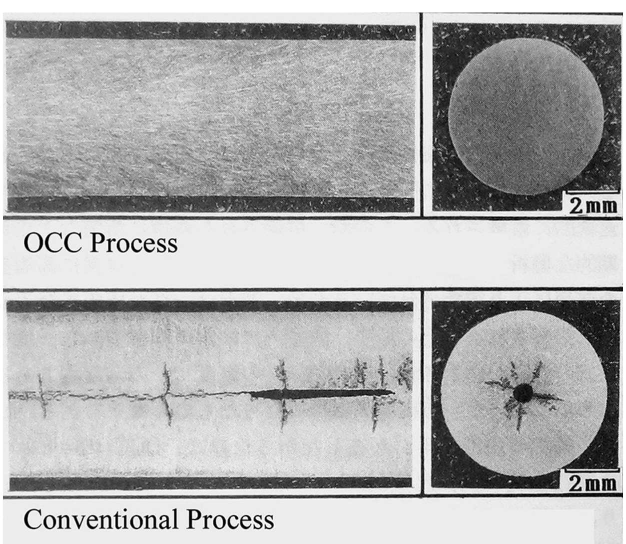

Fig. 13 Cross-sections of cast stellite rods (Co-30%Cr-12%W-2.5%C- < 3%Fe) produced by the OCC process and by a conventional continuous casting process (Ref 17)

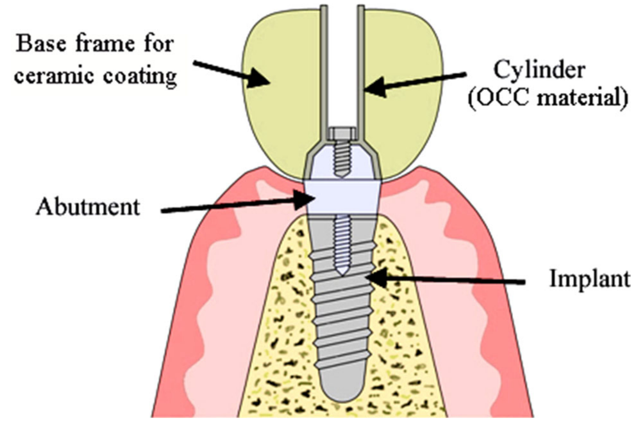

Fig. 14 Schematic diagram showing Co-Cr-Mo-based alloy cylinder (OCC material) being used in a dental implant. (Nihon Shika Kinzoku Co. Ltd.)

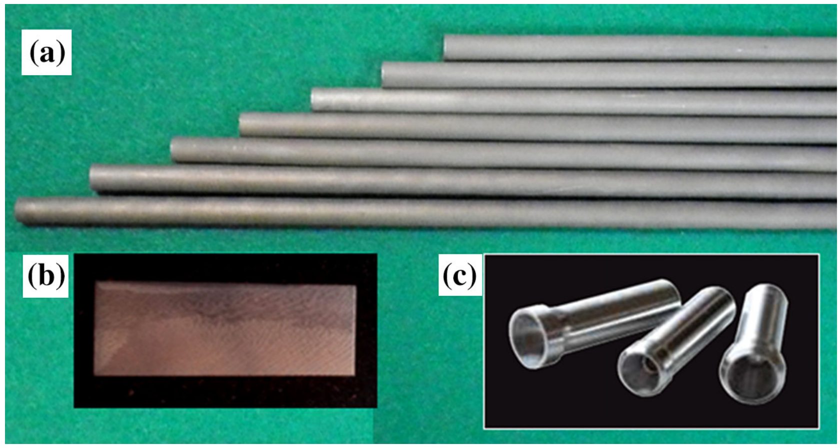

Fig. 15 (a) Co-Cr-Mo-based (dan-cobalt) alloy rods of 7 mm in diameter cast by the OCC process for dental applications, (b) unidirectionally structured material of OCC rod, and (c) cylinders made from cast rods for dental applications. (Osaka Fuji Corp. and Nihon Shika Kinzoku Co. Ltd.)

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