Continuously Cast Zinc Single Crystal Wires and their Mechanical Properties[†]

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Zinc wires of 2 mm diameter have been produced using the horizontal Ohno Continuous Casting process at casting speeds of 0.5, 1.7 and 2.8 mm/s. The effects of casting speed on crystal orientation and the mechanical properties of the cast wires have been studied. It was found that wires cast at all three speeds were single crystals. At the higher casting speeds (1.7 and 2.8 mm/s), the crystal orientation of the wires in the casting direction tended to align parallel to [0001]. At the lowest casting speed, 0.5 mm/s, the orientation of the cast wires was inconsistent. Some of the single crystal wires were ductile and could be bent repeatedly before fracture occurred. Cast wires with an angle between the (0001) cleavage plane and the wire axis of less than about 1.1 rad (65°) (wire axis near the [1211] direction) were significantly more ductile compared to those with an angle over 1.22 rad (70°) (wire axis near [0001]) which fractured after only a single bending. It was also found that wires with the axis close to the [1210] direction (a cleavage angle of approximately 0.6 rad (36°)) exhibited considerable ductility with tensile elongations as large as 350%.

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I. Introduction

By employing a heated mold continuous casting process which is known as Ohno Continuous Casting (OCC)⁽¹⁾⁽²⁾, many unique products have been generated. Such products include cored materials⁽³⁾⁽⁴⁾, aluminum wires containing optical fibers⁽⁵⁾, single crystal copper cables⁽⁶⁾, net-shape aluminum, high-copper alloy rods (25 ~ 45 mass%Cu)⁽⁷⁾, aluminum rare-earth alloy wires⁽⁸⁾, stellite alloy tubes with complex cross-sectional geometries⁽⁹⁾, and ductile bismuth wires⁽¹⁰⁾. Some of these materials are now produced on a regular commercial basis.

The general concept of the OCC process is that molten metal is introduced continuously into an externally heated mold and heat is extracted from the cast product by means of cooling device located near the mold exit. Thus, unidirectional solidification occurs along the casting direction at or near the mold exit. As a result, mold-strand friction is eliminated and this permits the production of small-diameter, net-shape, cast products without breakage. Since, heat flow is unidirectional, single crystal materials can be cast continuously within a specific casting regime. Recently, the feasibility of casting bismuth wires by the OCC process was examined⁽¹⁰⁾. Depending on the crystal orientation, it was found that ductile bismuth wires exhibited remarkable elongation

behavior, sometimes in excess of 100%. However, the control of the growth orientation has not been achieved with this process. Thus, in the present study, the effects of casting conditions on the crystal growth orientation have been studied using zinc metal and the bend formability as well as elongation properties of the cast wires have been examined.

II. Experimental Aspects

Figure 1 shows a schematic diagram of the melting and casting arrangement designed to apply the principle of the heated mold continuous casting process to the production of a small diameter wire. Approximately 1.2 kg of a zinc ingot of 99.99% purity was melted in the crucible, with temperature maintained at 713 K, and liquid zinc fed into the tundish continuously through a runner by lowering a level control device into the melt. At one end of the tundish, there is a 2 mm diameter, 3 mm long channel, through which the liquid metal exits into the cooling zone, to produce wires. To start casting, a stainless steel wire 2 mm in diameter with a tapered end was inserted into the channel in order to bring the liquid metal to the exit. After ensuring good contact between the steel wire and the liquid metal, the cooling water was turned on and casting initiated by moving the pinch rolls. The temperature of the channel was maintained at 708 K ± 1 K during casting. Wires approximately 2 mm in diameter and 1 m in length were produced during each casting operation with casting speeds of 0.5, 1.7, and 2.8 mm/s. The single crystal wires were sectioned into appropriate lengths for mechanical testing. The results were correlated with the growth orientation of the single crystals determined by electron chan-

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Fig. 1 Schematic diagram of the horizontal Ohno Continuous Casting system.

neling pattern (ECP) analysis and with the angle between the cleavage plane and the wire axis. This angle will be referred to as the cleavage angle.

III. Results and Discussion

1. Growth orientation

The effect of casting speed on growth orientation was examined by generating 8 to 12 specimens at each casting speed of 0.5, 1.7, and 2.8 mm/s for a total of 32 specimens. **Figure 2** shows the macrostructure of samples of cast zinc wires obtained from the starting end, and 200 mm away from the starting end, of the cast wires. It was found that at all casting speeds, after approximately 200 mm of casting, the wires became single crystal.

Yamamoto and Watanabe⁽¹¹⁾ also studied the effects of various growth conditions on the yield rate of a single crystal and the orientation distribution by producing zinc crystal rods (99.997% purity) 5–15 mm in diameter us-

ing the Bridgman method with growth speeds of 4.4×10^{-3} mm/s $\sim$ 2.4×10^{-1} mm/s. At the higher growth speed (e.g.: 2.4×10^{-1} mm/s), success in producing single crystals was less than 10% and at the lower casting speed (4.4×10^{-3} mm/s) it was 90% for rod of 5 mm in diameter. Under these growth conditions, single crystals of all orientations were obtained. However, the conditions most favored an orientation where the (0001) plane lay almost parallel to the rod axis⁽¹¹⁾.

Figure 3 shows the growth orientations of the wires produced by the OCC process at three different speeds. It is clear that at a casting speed of 0.5 mm/s, the growth orientation was inconsistent and there was no crystal with an axial orientation close to $[1\bar{1}00]$. The orientation became more consistent at the higher casting speeds (1.7 and 2.8 mm/s) and appeared to cluster near the $[0001]$ direction. These results indicate that the $[0001]$ direction is the preferred growth orientation at the higher casting speeds and in fact the most frequently observed cleavage angle was $1.22 \sim 1.57$ rad ($70^\circ \sim 90^\circ$) which in this case means that the (0001) basal plane lies almost perpendicular to the wire axis. These results significantly differ from those of Yamamoto and Watanabe.

2. Bend formability and elongation properties

To observe the degree of ductility as a function of crystal orientation, wire specimens were subjected to a simple 1.57 rad (90°)-bend test until fracture occurred. Since cast zinc wires were found to fracture parallel to the (0001) plane, as confirmed by ECP analysis, the number of bend cycles required for fracture was correlated with the cleavage angles in reference to the wire axis. The results are shown in **Fig. 4**. It is clear that the flexibility varies significantly with orientation. Wires with

Fig. 2 Macrostructure observed in longitudinal cross-section of specimens from (a) starting end and (b) 200 mm from the starting end, of the wires cast at 0.5 mm/s and 2.8 mm/s.

Fig. 3 Stereographic projection showing growth orientation of zinc single crystal wires cast at 0.5 mm/s (●), 1.7 mm/s (■), and 2.8 mm/s (▲).

Fig. 4 Relationship between number of bend cycles for wire fracture and cleavage angle.

a cleavage plane closer to perpendicular to the wire axis (e.g. a cleavage angle of more than about 1.2 rad (70°)) exhibited no ductility whereas those with a cleavage angle below 1.2 rad showed ductility which increased as the angle became smaller. Wires with a cleavage angle less than 1.1 rad (65°) showed significant ductility. Since the (0001) plane is both the slip and the cleavage plane, the (0001) plane, which lies normal to the direction of the applied stress, causes cleavage fracture more easily compared to the (0001) plane lying closer to the direction of stress. Thus, with lower angles more applied stress will be resolved along the slip plane promoting slip.

Since these aspects can be expressed in terms of tensile

Fig. 5 (a) Typical stress-strain curves for specimens with the growth orientation close to the [0001], [1213], and [1210] which corresponds to ①, ② and ③ respectively in Fig. 3. (b) Elongations versus cleavage angle.

elongation and cleavage angle, tensile tests were performed using specimens with known cleavage angles based on information from bend tests. The tests were conducted with a gage length of 50 mm and a cross-head speed of 1.67×10^{-2} mm/s. **Figure 5(a)** shows typical stress-strain curves for specimens known to have a growth orientation near the [0001], [1213], and [1210] direction (noted by ①, ②, and ③ in Fig. 3) which represents the cleavage angle of 1.54, 0.94 and 0.63 rad (88°, 54° and 36°) respectively. The elongation values were also correlated with the cleavage angles of the specimens tested as shown in Fig. 5(b). It is clear that there was little deformation in specimens having the (0001) plane positioned just or almost perpendicular to the wire axis. The stress-strain curve exhibited jagged irregularities, indicating that the specimen deformed by twinning. On the other hand, specimens with lower cleavage angles showed remarkable elongation, sometimes as much as 350%. The shear stress on the slip plane of specimens ①, ②, and ③ calculated using the yield stress values (Fig. 3) is approximately 1.7, 3.2 and 2.0 MPa respectively at the yield point. Although the values are small and vary by only a factor of 2 between ① and ③, the amount of deformation that can occur in the crystal depends on the relative values of stresses acting on slip, twinning, and cleavage planes. The normal stress on the basal plane of specimens ①, ②, and ③ is 10.5, 1.0, and 0.7 MPa respectively at the yield point. The critical resolved shear stress that causes slipping on the (0001)

plane in the $[11\bar{2}0]$ direction is 0.2–1 MPa⁽¹²⁾ and the critical normal stress for brittle cleavage is ~ 2 MPa⁽¹³⁾. Under these circumstances, specimen ① will easily fracture and specimen ③ will undergo plastic deformation by slipping before fracture. Observation of specimens after tensile testing revealed extensive slip lines, while specimen ① exhibited twin deformation bands that caused a small amount of deformation ($\sim 5\%$). The difference in values of yield stress and elongation between specimens ① and ③ are approximately 10 and 70 fold respectively, indicating strong orientation dependence.

Single crystal bismuth is known to exhibit similar behavior. Cleavage occurs with single bending when the angle of the basal plane relative to the direction of applied stress becomes larger than 1 rad (57°)⁽¹⁴⁾. In this regard, the brittle range for zinc crystal is much narrower than that for bismuth crystal since zinc shows brittle characteristics only when the angle of the (0001) plane with respect to the applied stress exceeds ~ 1.2 rad (70°).

IV. Summary

An experimental study was conducted in order to investigate the effects of casting conditions of the OCC process on crystal growth orientation of zinc single crystal wires. The bend formability and elongation properties of the cast wires have also been examined. The results are summarized as follows:

- (1) Using the OCC process it was possible to produce zinc single crystal wires 2 mm in diameter at casting speeds of 0.5, 1.7, and 2.8 mm/s;
- (2) At the faster casting speeds the growth orientation tended to be near the $[0001]$ direction;
- (3) Zinc single crystal wires exhibited marked anisotropy of deformation due to differences in growth orientation;
- (4) Wires with cleavage angles greater than about 1.2 rad (70°) exhibited essentially zero ductility. On the other hand, wires with cleavage angle less than 1.13 rad (65°),

exhibited remarkable elongation, in excess of 100% and sometimes as large as 350%.

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