Application of Nano-Polycrystalline Diamond to Wear Resistant Tools

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In recent years, the quality level required for diamond dies has risen along with an improvement in the precision of wire materials such as semiconductor bonding wires and medical wires. Requirements are increasing for wire characteristics, particularly wear resistance and properties to maintain roundness and wire surface roughness. In order to meet the needs, we have developed the BLPCD die using a nano-polycrystalline diamond (Sumidia binderless) developed by Sumitomo Electric Industries, Ltd. as its core material. This paper reports the performance evaluation results.

Keywords: wire drawing, diamond die, nano-polycrystalline diamond, bonding wire, medical wire

1. Introduction

Wire drawing refers to the process of reducing the diameter of a wire made of metal or other material by plastic deformation to a target diameter.[1], [2]

A diamond die is a tool for wire drawing (Fig. 1). It is used to draw various types of metal wires by taking full advantage of the characteristics of diamond, the hardness of which is the highest of all substances.

Natural single-crystal diamonds (natural diamond: ND), artificial single-crystal diamonds (high-pressure high-temperature diamond: HPHT), and sintered diamond (polycrystalline diamond: PCD) are mainly used as the core materials in diamond dies.

We excel in high-precision and high-quality machining of small diameter dies and extremely small diameter dies (φ0.1 µm or less). Our products are highly evaluated by drawn wire manufacturers.

Recently, the precision requirements for wires, such as semiconductor bonding wires*1 and medical wires, have been becoming more stringent. Thus, the level of quality required of diamond dies has risen.

There has been growing demand for improving the characteristics of these wires particularly wear resistance and properties to maintain roundness and wire surface roughness.

To meet such demand, we have developed a new binderless PCD die ("BLPCD die") and evaluated its performance. The BLPCD die uses a nano-polycrystalline diamond (Sumidiabinderless)[3]–[5] developed by Sumitomo Electric Industries, Ltd. as the core material of the die. This paper shows that the BLPCD die is superior to HPHT and PCD dies across all the three factors mentioned earlier.

2. Structure of a Diamond Die

A diamond die mainly consists of diamond (i.e., core material), metal sintered compact (which secures the diamond in the center of the die), and a case material that supports them (Photo 1).

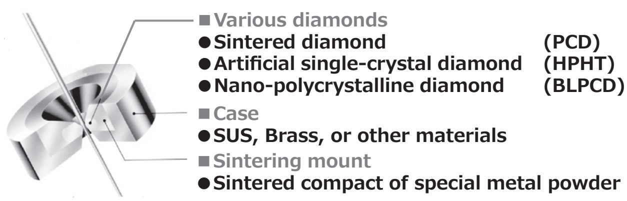

Photo 1. Structure of a diamond die

The wire processing area is hourglass shape. It consists of a bell, approach, reduction, bearing, back relief, and exit, in that order, from the wire receiving area of the die (Fig. 2).

High quality must be ensured, in particular, for fabrication of the reduction and bearing, as they come into

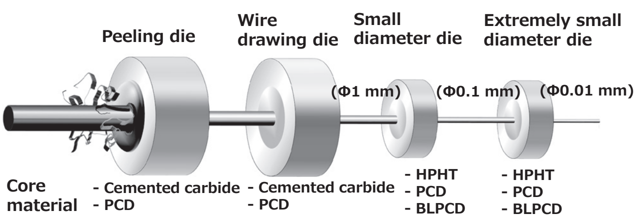

Fig. 1. Diamond die

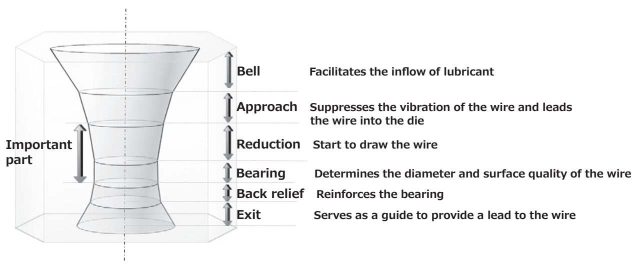

Fig. 2. Shape in a die

contact with the wire subject to drawing, and thus significantly affect the quality of the final product.(1)

3. Basic Performance of BLPCD Die and Evaluation in Wire Drawing

To evaluate the basic performance of a BLPCD die, we compared its wire drawing performance with that of HPHT and PCD die.

The common items for wire drawing conditions are shown in Table 1.

Table 1. Wire drawing conditions

Wire drawing machine	Wire drawing machine	Non-slip type single die wire drawing machine
	Wire drawing speed	600 m/min
	Back tension	5 cN
	Number of dies	1
	Lubricant	Mineral oil-based lubricant
Die	Die hole diameter(D)	0.080 mm
	Reduction angle	10±2°
	Bearing length	30±10%D
	Area reduction rate setting	13.5%
	Core material	BLPCD or PCD or HPHT
Core wire	Diameter of the core wire	0.086 mm
	Material	SUS304

3-1 Wear resistance

As the die hole becomes worn, its diameter increases, resulting in an increased diameter for the processed wire. For this reason, the capability to maintain the die hole diameter for an extended period is one of the most important factors determining the service life of a die until replacement.

Figure 3 shows the results of an investigation of the changes in wire diameter based on sampling of wires drawn quantitatively using various dies.

The wire diameter was measured by laser interference fringe diffractometry. The wire circumference was measured at 250 or more points, and the mean value was calculated as the wire diameter.

For the BLPCD and PCD dies, no significant expansion of the wire diameter was observed after wire drawing. For the HPHT die, expansion of the wire diameter was observed immediately after commencement of the wire drawing (from a wire drawing distance of 10 km). We believe that the results strongly reflect the characteristics of BLPCD whose hardness surpasses that of single-crystal diamonds.

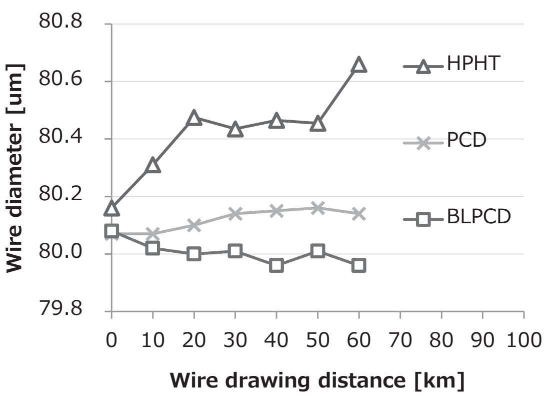

Fig. 3. Wear resistance of diamond dies

3-2 Properties to maintain roundness

An important factor that determines wire drawing performance and the characteristics of the final product (i.e., drawn wire) is decreased roundness of the wire cross section.

The technique described above (3-1) was used to measure the wire diameter, and the difference between the maximum and minimum measurement values (at 250 points or more) was calculated as roundness.

As shown in Fig. 4, the roundness of wires drawn by the BLPCD and PCD dies hardly changed for a long wire drawing distance, remaining almost constant. For the HPHT die, roundness decreased rapidly in the initial phase of wire drawing (at a wire drawing distance of 10 km).

This is attributed to a wear mode dependent on crystal orientation specific to single-crystal diamonds. BLPCD and PCDs are not affected by crystal orientation dependence because they are polycrystalline materials, which can maintain roundness for an extended period.

Photo 2 shows an example of drawing wire cross sections after the same distance using an ND die and a BLPCD die.

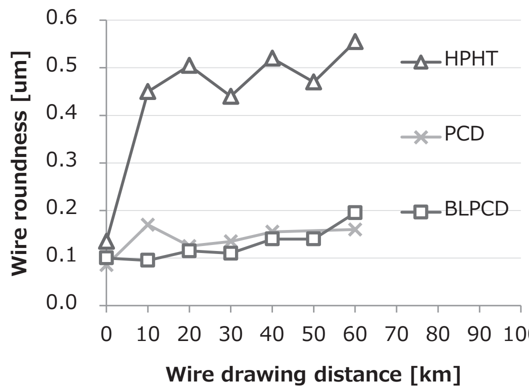

Fig. 4. Properties of diamond dies to maintain roundness

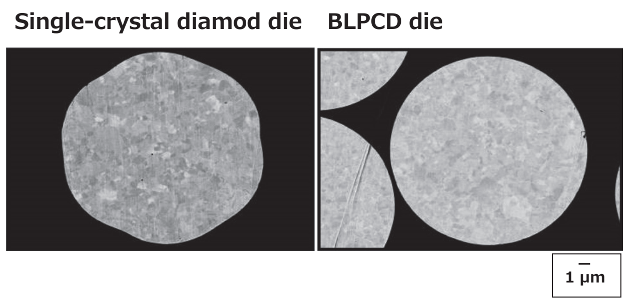

Photo 2. Wear modes dependent on the crystal orientation

On one hand, as shown in Photo 2, the shape of the wire drawn by the ND die reflects the wear mode due to crystal orientation dependence. The cross section of the wire is deformed to a polygon. On the other hand, the cross section of a wire drawn by the BLPCD die maintains roundness.

3-3 Properties to maintain wire surface roughness

Finally, we evaluated the surface roughness of wires after drawing. In wire drawing, it is important to maintain a smooth wire surface condition for an extended period.

An increase in surface roughness causes such problems as an increase in frictional resistance, color change, and plating delamination, which are likely to adversely affect the characteristics of the final product.

The wire surface roughness at each quantitative wire drawing point was measured using a laser microscope and evaluated using the Ra value*[2] (Fig. 5).

The images of the wire surface at each point are shown in Photo 3.

Figure 5 shows that the BLPCD die maintained the smoothest wire surface condition for an extended period, followed by the HPHT and PCD dies.

The surface roughness of the PCD die started to decrease early. Presumably, the diamond grains and binder, which came off under load during wire drawing, were caught in the processing area for wire drawing, and a local load applied to the wire surface resulted in scratches.

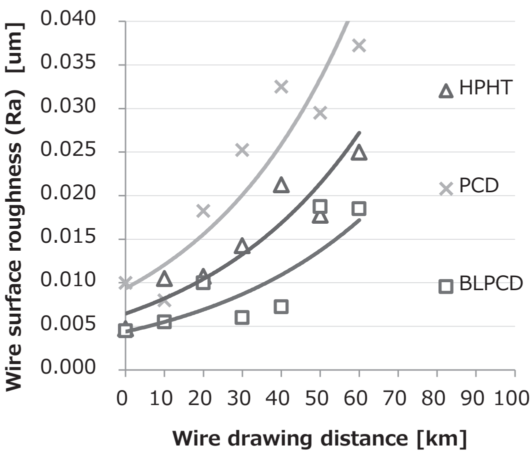

Fig. 5. Properties of diamond dies to maintain wire surface roughness

As Photo 3 shows, multiple stripe-shaped scratches were observed on a wire drawn by the PCD die at the 30 km point.

On the other hand, BLPCD is free from inclusions at the grain boundary. This prevents grains from coming off, and similar problems are less likely to occur.

The surface of the wire drawn by the HPHT die maintained a relatively smooth condition. Stripe-shaped scratches similar to those caused by the PCD die were not observed. However, as discussed above (3-2), the wear mode is highly dependent on the crystal orientation. The wire became flat due to uneven wear (Photo 3).

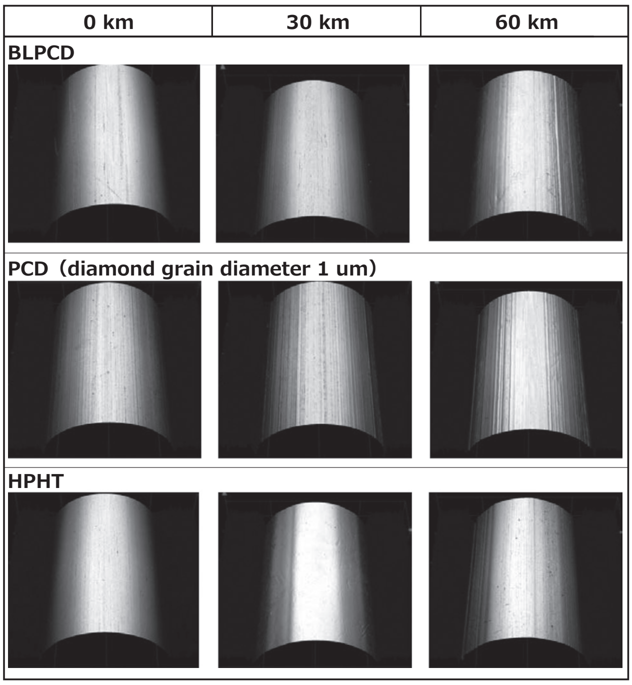

Photo 3. Wire surface condition after drawing

4. Future Development

4-1 Development of BLPCD dies for shaped wires

Wires with a square cross section are often used for motor windings and other products. These wires help reduce the gap between wires compared to conventional round wires when they are used in windings.

In line with the downsizing of equipment, there has been growing demand for these wires because high density coils can be manufactured with smaller capacity.

The high tool performance demonstrated by the BLPCD die can also be applied to these shaped wires*[3] in addition to round wires. We have launched a development project in this regard.

At present, PCD dies are mainly used for shaped wires (Photo 4). For those that contain binders in the grain

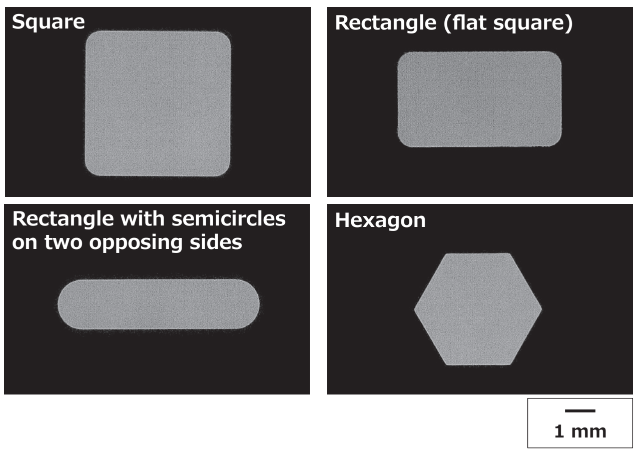

Photo 4. Die hole shapes for different shaped wires

boundary, it becomes difficult to control the surface roughness when the angles are small.

Additionally, single-crystal diamond dies are dependent on the crystal orientation and subject to uneven wear. Thus, they are considered to be inappropriate for shaped wires whose precision on each side is important.

As confirmed in the wire drawing evaluation in this paper, the basic performance of a BLPCD die is likely to solve all of these issues.

5. Conclusion

This paper confirms that the performance of a BLPCD die is superior to that of HPHT and PCD dies in terms of wear resistance and properties to maintain roundness and wire surface roughness.

BLPCD dies offer an extended service life, and have the potential to cut die management costs and achieve the processing of cemented carbide wires that are difficult to process using conventional single-crystal diamond dies. We believe that BLPCD dies will contribute to the future development of the wire drawing industry.

Technical Terms

∗1 Bonding wire: A wire used to connect an electrode of a transistor or integrated circuit with an electrode of a printed wiring board or semiconductor package

∗2 Ra value: Mean value of the absolute value of a roughness curve for the reference length

∗3 Shaped wire: A wire whose cross section is not round (e.g., square, rectangle [flat square], and rectangle with semicircles on two opposing sides)

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