



Shaped Dies Made of Diamond for Smaller and Lighter Automotive and Electronic Components

Akihito ONO*, Yuichiro SEKI, Kouichiro KIMURA, Tomohiro FUKAYA, and Hiroki KAWAHARA

In recent years, demands for miniaturization and improved energy efficiency in automotive motors and electronic components have intensified. One effective approach to these demands is increasing the space factor of coil windings by utilizing wires with non-circular cross-sections, which require shaped dies. However, achieving high precision for automotive applications and realizing ultra-small shaped dies suitable for miniaturized electronic components have been challenging with existing technologies. Therefore, A.L.M.T. Corp. has developed shaped dies made of diamond, achieving a high-precision hole diameter tolerance of $\pm 1 \mu\text{m}$ and high-quality inner surfaces with surface roughness of $R_a 10 \text{ nm}$ for automotive use. For electronic components, A.L.M.T. Corp. has mass-produced ultra-small shaped dies with hole diameters ranging from $30 \mu\text{m}$ to $100 \mu\text{m}$, and established a design methodology combining computer-aided engineering (CAE) simulation with actual wire drawing experiments. This paper reports these developments.

Keywords: shaped die, diamond, wire drawing, motor coil, miniaturization and weight reduction

1. Introduction

Wire drawing is a metalworking process in which metal wire is pulled through a hole in a tool called a die to form the desired diameter and cross-sectional shape.^{(1),(2)} This is a processing method applied to a wide variety of products, including electric wires, springs, medical wire, and bonding wires. Diamond is a core material for dies used in this process and exhibits excellent performance. Due to its extremely high wear resistance, hardness, and thermal conductivity, diamond enables long-lasting and high-precision wire drawing. A.L.M.T. Corp. possesses advanced technology for manufacturing diamond dies. As one of the world's leading manufacturers, we have contributed to the development of industrial infrastructure by supplying high-quality diamond dies.

Demands for miniaturization and improved energy efficiency in automotive motors and electronic devices have intensified with rapid progress in vehicle electrification and enhanced functionalities of electronic components. Increasing the space factor*¹ of coil windings using wires with non-circular cross-sections has attracted attention,⁽³⁾ and the requirement levels for shaped dies used in their production have risen rapidly. Against this background, for automotive motors, further improvements in hole diameter accuracy and inner surface quality of shaped dies are demanded. For electronic components, there is a growing need for ultra-small sized shaped dies with hole diameters under $100 \mu\text{m}$, which existing technologies find difficult to realize. Furthermore, optimal combination design of multiple dies required for wire drawing of wires with non-circular cross-sections is also a challenging task that demands advanced technical expertise.

Based on these circumstances, we have been engaged in the development of shaped dies made of diamond. This paper introduces our achievements in high-precision and high-quality shaped dies for automotive applications,

small-diameter shaped dies for electronic components, and the establishment of a design methodology combining computer-aided engineering (CAE)*² with actual wire drawing experiments.

2. What Are Shaped Dies?

2-1 Differences between round dies and shaped dies

Dies used in wire drawing are broadly classified into two types based on the cross-sectional shape of their holes. Those with a perfectly circular hole cross-section are called round dies, while those with non-circular cross-sectional shapes such as square or hexagonal are called shaped dies (Fig. 1).

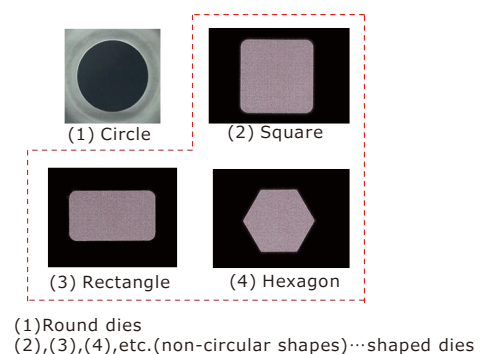


Fig. 1. Various dies hole shapes

Among dies, round dies are mainstream and are used in a wide range of applications. Because their holes are circular, the stress distribution during processing tends to

be uniform, allowing for stable wire drawing. On the other hand, shaped dies have polygonal hole cross-sections, which cause complex material flow during processing, making it technically challenging to maintain shape accuracy and surface quality. In particular, controlling the shape of corners is difficult, and manufacturing high-precision shaped dies requires advanced processing techniques and quality control.

2-2 Relationship between shaped cross-sections and space factor

When coils are formed using round wire, voids occur between the wires, resulting in a lower space factor. In contrast, when shaped wires such as square or hexagonal wires are used, adjacent wires contact each other along their surfaces, significantly reducing voids and improving the space factor (Fig. 2).

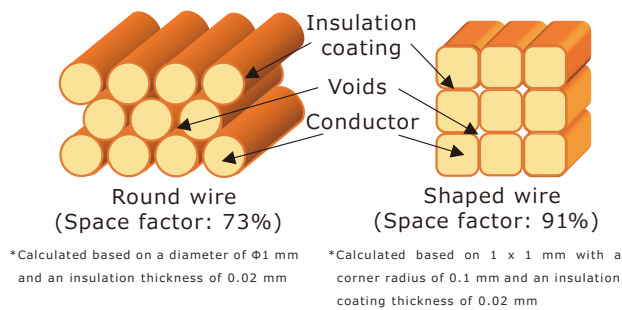


Fig. 2. Comparison of the space factor of round wire and shaped wire during coil forming

2-3 Applications to automotive motors and electronic components

Improving the space factor leads to enhanced performance of automotive motors and electronic components in the following ways.

In automotive motor applications, increased space factor reduces the electrical resistance of motor coils, thereby decreasing the current required to achieve the same output. Furthermore, the same output performance can be realized with a smaller coil volume, contributing to the miniaturization and weight reduction of the motor itself.⁽⁴⁾ This effect is particularly important in hybrid electric vehicles (HEVs) and electric vehicles (EVs), as downsizing the drive motor impacts driving range and vehicle performance.

In electronic component applications, magnetic components such as inductors and transformers can achieve the same inductance with smaller cores. As the functional enhancement and miniaturization of electronic components accelerate, contributing to size reduction directly enhances product competitiveness.

3. Development of Shaped Dies for Automotive Motors

We have developed proprietary polishing technology to improve the quality of shaped dies for automotive

motors. In this chapter, we present the results of improvements in the inner surface condition and hole diameter accuracy of the dies, as well as the verification of their effects in actual wire drawing processes.

3-1 Improvement of inner surface condition and hole diameter accuracy

The surface roughness of the die's inner surface significantly affects the wire's surface quality and frictional resistance during wire drawing. When the inner surface roughness is large, fine scratches are transferred onto the wire surface during drawing, increasing the risk of wire breakage and degrading wire quality. Additionally, hole diameter accuracy is a parameter that directly determines the cross-sectional dimensions of the wire after passing through the die. In conventional shaped dies, manufacturing difficulties have generally limited hole diameter tolerances to the order of several micrometers.

We have simultaneously addressed these two challenges through the development of proprietary polishing technology. Improved accuracy in process control during the polishing step contributed to both the inner surface condition and hole diameter accuracy. Regarding the inner surface condition, we succeeded in finishing the die's inner surface to a mirror-level finish. Figure 3 shows a comparison of die inner surfaces between conventional and improved products. While fine irregularities are observed on the inner surface of the conventional product, the improved product exhibits a smooth mirror finish. The surface roughness improved significantly from Ra 61 nm for the conventional product to Ra 10 nm for the improved product, achieving a drastic smoothing of the inner surface. Regarding hole diameter accuracy, the advancement in polishing technology enabled achieving hole diameter tolerance of $\pm 1 \mu\text{m}$. This suppresses variation in wire dimensions after drawing, contributing to the stabilization of coil space factor and homogenization of motor characteristics.

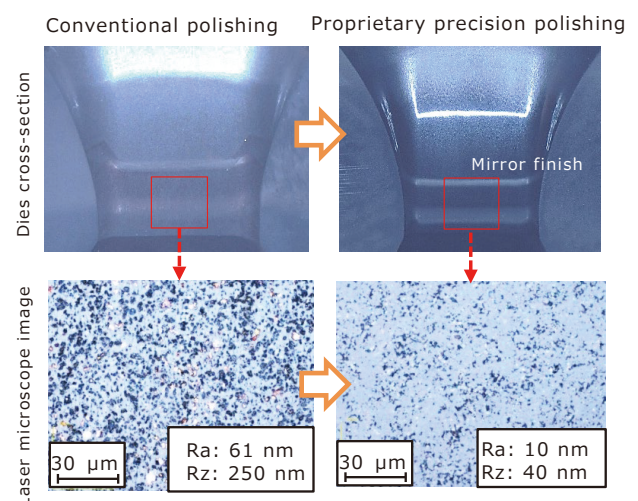


Fig. 3. Comparison of the inner surfaces of shaped dies

3-2 Wire drawing results

To verify the effects of improved die performance in actual wire drawing, wire drawing tests were conducted using the improved shaped dies. Table 1 shows the wire drawing conditions.

Figure 4 shows surface micrographs of wires drawn using conventional and improved dies. Fine scratches were observed on the wire surface when using conventional dies, whereas improved dies produced a smooth surface. Figure 5 presents roughness comparison data of the wires. The roughness was Ra 114 nm for the conventional dies and Ra 39 nm for the improved dies, confirming a significant improvement in wire surface quality. The smoothing of the surface leads to uniform insulation coating formation on the wire surface, which is expected to improve insulation reliability. Based on the above, our proprietary polishing technology was demonstrated to contribute to improving die performance and enhancing wire quality in actual wire drawing.

Table 1. Wire drawing conditions

Wire drawing machine	Drawing machine	Drawing bench
	Drawing speed	20 m/min
	Number of dies	1
Dies	Dies hole size	2.000 × 3.000 mm Corner radius: 0.3 mm
	Reduction angle	16 ± 2°
	Bearing length	0.6 mm
	Diamond material	PCD*3
Initial wire	Material	Pure copper
	Wire size	2.200 × 3.200 mm

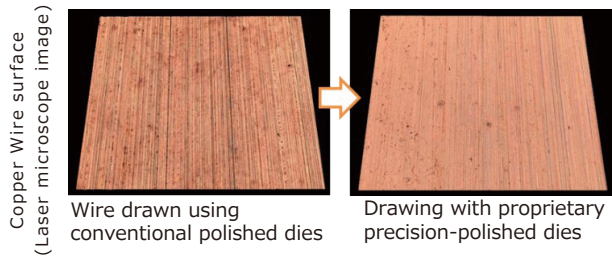


Fig. 4. Comparison of copper wire surfaces after dies drawing

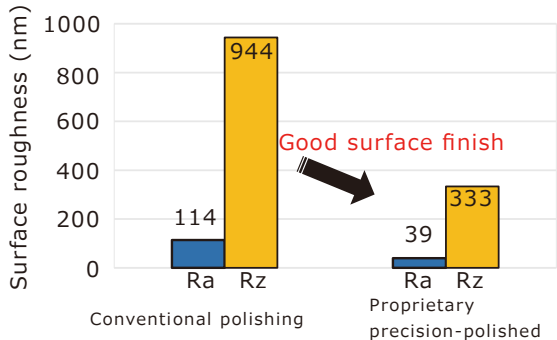


Fig. 5. Comparison of copper wire surface roughness after wire drawing

4. Development of Small-Diameter Shaped Dies for Electronic Components

4-1 Technical challenges of small-diameter shaped dies

Due to the demand for miniaturization of electronic components described in Section 2-3, the need for small-diameter shaped dies with hole diameters under 100 μm has been increasing. However, when downsizing the hole diameter of shaped dies, there are two major technical challenges.

First, as the hole diameter decreases, it becomes significantly more difficult to accurately form the desired shaped cross-sectional profile. Second, in controlling the corner shape, the smaller the hole diameter, the more difficult it is to miniaturize and homogenize the corners. If the corner shape is uneven, the risk of wire breakage and shape defects increases due to stress concentration during wire drawing. Conventional technologies have struggled to address these challenges, presenting a technical hurdle to the commercialization of shaped dies with hole diameters under 100 μm.

4-2 Realization of small-diameter shaped dies

We have developed proprietary microfabrication technology and succeeded in commercializing small-diameter shaped dies with hole diameters ranging from 30 μm to 100 μm. This achievement addresses a hole diameter range that had previously been difficult to commercialize.

Figure 6 shows the scanning electron microscope (SEM) images of the inner surfaces of the commercialized small-diameter shaped dies. The desired cross-sectional shapes are confirmed to be formed with high precision. Additionally, the corner sections have been finely formed with a minimum corner radius (corner R) of 5 μm. These results demonstrate that our microfabrication technology ensures shape accuracy and corner quality even in the small-diameter range.

With these products, wire drawing of shaped wires with non-circular cross-sections has become possible even in the ultra-fine diameter range that was previously limited to round wires. This provides a new option for further miniaturization and functional enhancement of electronic components.

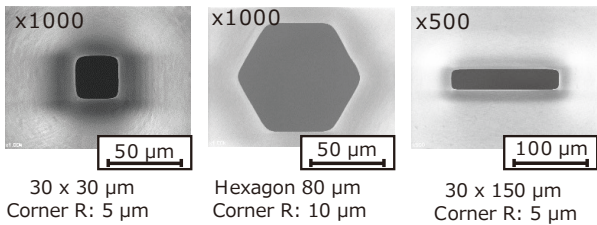


Fig. 6. Examples of prototype small-diameter shaped dies

5. Combination Design of Shaped Dies Using CAE

Sections 3 and 4 discussed the improvement of processing quality of individual dies. On the other hand, in wire drawing of wires with non-circular cross-sections, it is

difficult to form the desired shaped cross-section from round wire in a single step, so it is common to form the shape gradually using multiple dies. At this time, the design of the combination—how to set the reduction in area*⁴ and shape of each die—becomes a key factor that determines the shape accuracy of the wire and the stability of wire drawing. Traditionally, this combination design has heavily relied on the experience of engineers and repeated prototyping, requiring a great deal of man-hours to find the optimal conditions. We have established a design methodology that uses CAE to derive the optimal combination conditions. This section describes our approach.

5-1 Overview of the analysis method

In this study, elastic-plastic finite element analysis was used to simulate the wire drawing process. The analysis model consisted of the die modeled as a rigid body and the wire modeled as an elastic-plastic body. The Coulomb friction model*⁵ was applied to the friction between the die and the wire, and the friction coefficient was set based on actual processing conditions. As evaluation indicators, corner R measurements and drawing force of the wire after drawing were used.

5-2 Optimization of combination conditions using CAE

In this study, the target was shaped wire with a 45 x 45 μm square cross-section and a corner R of 10 μm , assuming wire drawing using two dies. The reason for focusing on the reduction in area in the combination design process was that it is a parameter that greatly influences wire drawing, impacting both formability and drawing force. In this study, other parameters (die angle, bearing length, etc.) were fixed, and the reduction in area of the first and second dies was set to equal values. These values were varied systematically from 5% to 30%, and their effects were evaluated.

Figure 7 shows the relationship between reduction in area and corner R. A tendency for the corner R to decrease with increasing reduction in area was confirmed. This is considered to be because, as the reduction in area increases, plastic flow of the material is promoted, improving material filling into the die hole shape. On the other hand, Fig. 8 shows the relationship between reduction in area and drawing force. A tendency for the drawing force to increase with increasing reduction in area was confirmed. Since excessive increase of drawing force raises the risk of wire breakage, there is an upper limit to increasing the reduction in area.

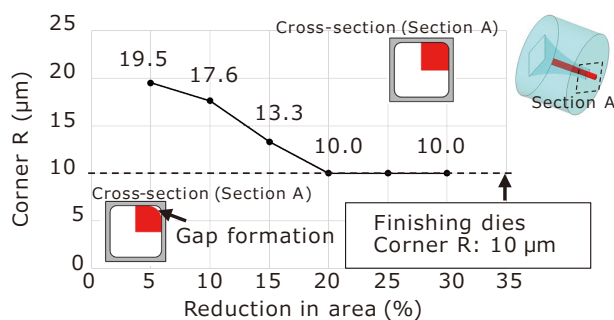


Fig. 7. Changes in corner R based on surface reduction in area

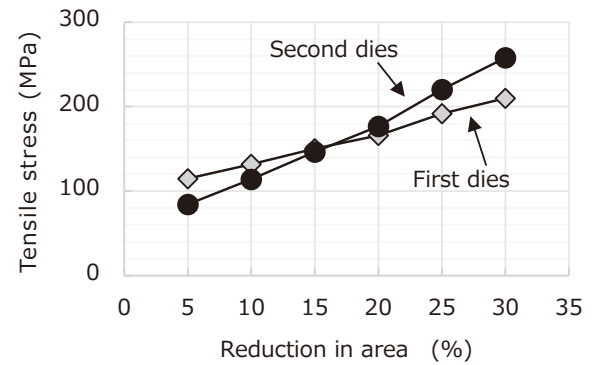


Fig. 8. Change in tensile stress as a function of Reduction in area

Based on these results, a reduction in area of 20% was judged to be the optimal condition, as it provides a corner R close to the target value while keeping the drawing force within a range that enables stable wire drawing.

5-3 Verification by wire drawing

To verify the validity of the combination conditions derived by CAE in Section 5-2, wire drawing tests were conducted using actual equipment. Table 2 shows the wire drawing conditions.

Figure 9 shows the SEM images of the wire after drawing. Successful wire drawing of small-diameter shaped wires with good surface condition was achieved. Figure 10 shows the measurement results of the corner R. The measured corner R was 9.6 μm , showing good agreement with both the target value of 10 μm and the predicted value of 10 μm from the CAE analysis. No defects such as wire breakage occurred during drawing, and stable wire drawing was realized.

Based on the above, the effectiveness of the combination design method utilizing CAE was demonstrated by the actual wire drawing. By using this method, the combination design process, which had conventionally relied on repeated prototyping, can be made more efficient, enabling the accommodation of various shaped wire cross-sections.

Table 2. Wire drawing conditions (drawing of 45 x 45 μm wire)

Wire drawing machine	Drawing machine	Non-slip type
	Drawing speed	100 m/min
	Back tension	1 cN
	Lubricant	Mineral oil-based lubricant
Dies	Finishing dies	45 x 45 μm Corner R: 10 μm
	Intermediate dies	50 x 50 μm Corner R: 10 μm
	Reduction angle	16 $\pm$ 2°
	Reduction in area	20%
Initial wire	Diamond material	BLPCD
	Material	Pure copper
	Wire size	Φ62 μm

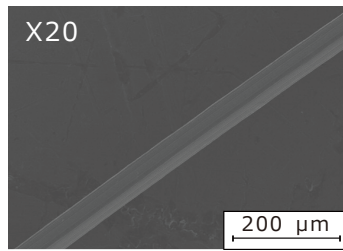


Fig. 9. Wire after drawing (45 x 45 μm)

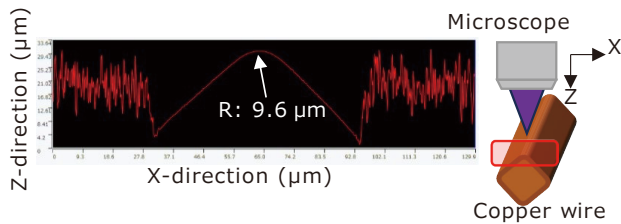


Fig. 10. Measurement results of copper wire corner after drawing

6. Conclusion

This paper presented the development of diamond shaped dies for automotive motors and electronic components, together with a CAE based combination design methodology.

For automotive motor applications, our proprietary polishing technology achieved mirror-finished inner surfaces and hole tolerances of $\pm 1 \mu\text{m}$. Drawing tests confirmed markedly improved wire surface quality, which is expected to stabilize coil space factor and homogenize motor characteristics. For electronic components, our microfabrication technology enabled the commercialization of shaped dies with hole sizes of 30–100 μm , previously unattainable; SEM observations verified that shape accuracy and corner quality are maintained in this range. In the CAE-based design, elastic-plastic finite element analysis systematically evaluated the effect of reduction in area on corner R and drawing force, and the derived optimal conditions showed good agreement with actual drawing results.

Future work will focus on further precision and miniaturization, broader CAE application, and adaptability to diverse cross-sectional shapes, thereby supporting automotive electrification and electronic device advancement.

Technical Terms

- *1 Space factor: The proportion of current-carrying conductor area to the cross-sectional area of the coil or motor slot.
Space factor (%) = (Total conductor cross-sectional area/Slot cross-sectional area) $\times$ 100
- *2 Computer aided engineering (CAE): Technology for evaluating and verifying product performance and behavior in advance during design and development.
- *3 Polycrystalline diamond (PCD): A consolidated material produced by sintering diamond powder with a metal binder under high pressure and temperature.
- *4 Reduction in area: The percentage decrease in wire cross-sectional area before and after passing through the die. A larger value promotes plastic flow and improves formability, but increases drawing force and the risk of wire breakage.
Reduction in area (%) = $((A_0 - A_1)/A_0) \times 100$
where A_0 and A_1 are the cross-sectional areas before and after the dies, respectively.
- *5 Coulomb friction model: A model in which frictional force between contacting bodies is proportional to the normal force acting perpendicular to the contact surface.

References

- (1) The Japan Society for Technology of Plasticity, Drawing-Everything from Bar and Wire to Tube (in Japanese), pp.1-18 (2017)
- (2) T.Arai et al., Diamond Tool Manual (in Japanese), Diamond Industry Association, pp.130-140
- (3) Yu Zhao, Dawei Li, Tonghao Pei, Ronghai Qu, "Overview of the Rectangular Wire Windings AC Electrical Machine," CES Transactions on Electrical Machines and Systems, Vol.3, No.2, pp.160–169 (June, 2019)
- (4) P. S. Ghahfarokhi, "Hairpin Windings for Electric Vehicle Motors: Modeling and Investigation of AC Loss-Mitigating Approaches," Machines, Vol.10, No.11, 1029 (2022)

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Contributors The lead author is indicated by an asterisk (*).**A. ONO***

• Assistant Manager , A.L.M.T. Corp

**Y. SEKI**

• Manager , A.L.M.T. Corp

**K. KIMURA**

• CTO, ESTEVES GROUP

**T. FUKAYA**

• Department Manager, A.L.M.T. Corp

**H. KAWAHARA**

• A.L.M.T. Corp

