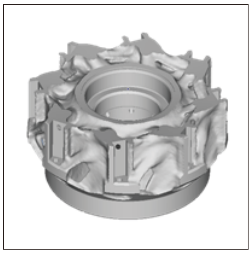


Lightweight and Through-Coolant Cutting Tools Produced Using Additive Manufacturing

Tomoya YOSHIDA*, Kiliha KATAYAMA, Yuki RIKISO, Yuka FUKUNAGA, and Daisuke MURAKAMI

Cutting tool requirements change from year to year. In the automotive industry, the shift to electrification is increasing the demand for lightweight tools that enable highly efficient machining of aluminum alloy components. In the aerospace industry, the use of difficult-to-machine materials such as nickel-based alloys and titanium alloys to reduce engine noise and fuel consumption is increasing, as is the need for through-coolant tools that can efficiently cool cutting edges when machining these materials. In response to these shifting market demands, we are employing additive manufacturing (AM) to develop innovative cutting tools. This time, by utilizing AM to form a complex internal structure, we have realized a lightweight cutter for aluminum machining that maintains the rigidity of the cutting edge while reducing the weight. Additionally, we have developed a cutter for difficult-to-cut materials that enables uniform cooling of the entire cutting edge by optimizing the internal flow path.

Keywords: Additive Manufacturing (AM), 3D printer, topology optimization, machining of aluminum alloys, machining difficult-to-cut materials

1. Introduction

Needs for cutting tools are changing year by year. In the automotive industry, where electrification is progressing, there is a demand for lighter weight tools to achieve more efficient machining of aluminum alloys, the main material used in electric vehicle parts. In the aircraft industry, the use of difficult-to-machine materials such as nickel-based alloys and titanium alloys with excellent heat and corrosion resistance is increasing, and the higher temperatures at the machining point require through-coolant tools that can cool cutting edges more effectively.

To respond to these changes in market needs, we are developing innovative cutting tools utilizing additive manufacturing (AM), a technology that slices 3D model data into multiple 2D layers as shown in Fig. 1, and uses a 3D printer to stack materials layer by layer based on that data to create a 3D object. AM is extremely effective in optimizing the internal coolant channels and reducing weight without compromising rigidity, because it can form complex internal structures that are difficult to achieve with conventional removal processes. This paper reports on the development of a lightweight cutter body for aluminum machining and a long-edge cutter body for machining difficult-to-cut materials using AM.

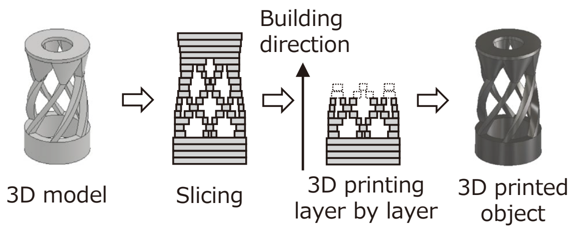
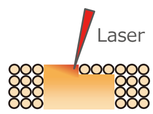
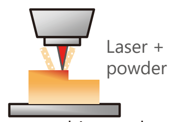


Fig. 1. AM process overview

2. AM Methods and Their Features

There are two main AM methods for metals (Table 1[(1)-(3)]): selective laser melting (SLM), in which metal powder is spread flat and melted and solidified by irradiating with a laser on the necessary parts, and directed energy deposition (DED), in which a metal powder stream is melted and solidified with the base material by laser. In this study, SLM was used to print the cutter body for better accuracy. The metal material used was maraging steel for sufficient rigidity and strength.

Table 1. Common metal AM methods

	SLM	DED
AM methods	 Laser melting and solidification for each powder layer	 Laser melting and solidification of the focused powder stream
Accuracy	Up to 0.2 mm	Up to 2 mm
Surface roughness	Ra 4-20 μm	Ra 10-20 μm
Print size	Up to 400 mm	Up to 1 m

Although 3D printers are considered to be able to easily create any shape as long as they have 3D data, in reality, deformation occurs due to the heat applied during printing, requiring ingenuity to obtain the desired shape. In SLM, shapes called overhangs, such as those shown in Fig. 2, trap heat from the laser and tend to warp easily due to shrinkage during cooling, as there is no restraint from the lower layers. Generally, when the overhang angle is 45° or less with respect to the building direction, the warping is so significant that printing cannot be continued. To minimize warping, it is necessary to build low-density structures known as supports under overhangs. However, these supports must be removed after printing, increasing the overall process costs. In addition, the support inside the structure is difficult to remove. Therefore, it is desirable to design a shape that requires as little support as possible.

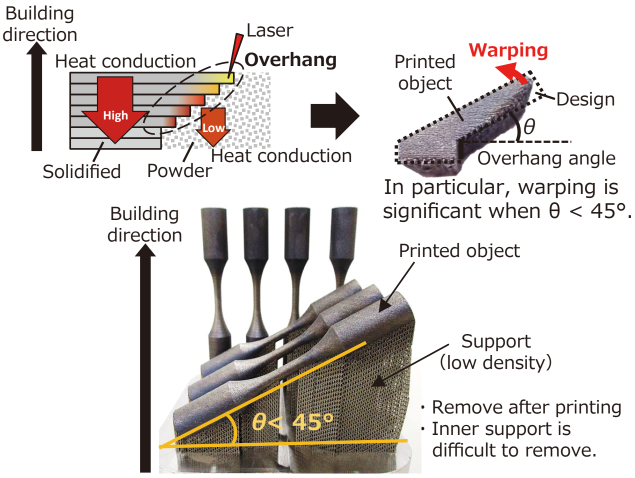


Fig. 2. Overhang shape and support material

Furthermore, AM tends to be more expensive than traditional machining due to the use of costly metal powders compared to cast or forged metals, along with high depreciation costs resulting from relatively low production efficiency. Thus, AM should be used for shapes that cannot be produced with traditional machining. We have developed lightweight cutters for aluminum machining and long-edge cutters with enhanced coolant channels for difficult-to-cut materials, both of which have unique structures that cannot be produced using conventional manufacturing methods.

3. Lightweight Cutter Body for Aluminum Machining

Since aluminum alloys have low cutting resistance and cutting heat during machining, it is common to use large-diameter cutters at high rotational speed for highly efficient machining. However, small machining centers often used for aluminum alloy machining have weight limitations on the spindle to which the tools are attached, and large-diameter steel cutters may not be used. While aluminum alloy cutter bodies are often used to reduce weight, their lower rigidity and hardness compared to steel bodies result in elastic deformation during machining and wear from chips. We attempted to reduce the weight of our steel cutter body ALNEX (ANXS 16000R type, diameter 100 mm) for aluminum alloy machining from 1.9 kg to 1.0 kg or lower, which is the same level as that of an aluminum alloy cutter body, by utilizing AM.

Topology optimization was used as a method for reducing weight. It calculates the material distribution that maximizes stiffness at a target weight for a set load and constraint conditions as shown in Fig. 3.

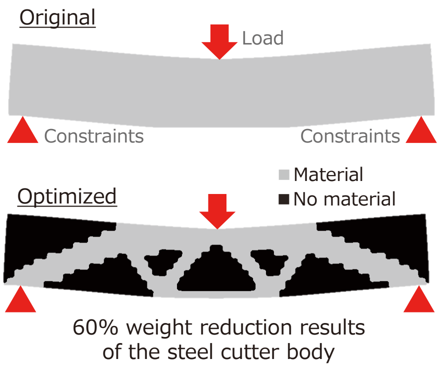


Fig. 3. Topology optimization

We performed topology optimization on the current steel cutter body under load and constraint conditions for front face milling. As a result, a lightweight cutter body shape equivalent to 0.9 kg in weight was obtained as shown in Fig. 4, and stress analysis confirmed that it is approximately 1.5 times more rigid than a solid aluminum alloy body as shown in Fig. 5.

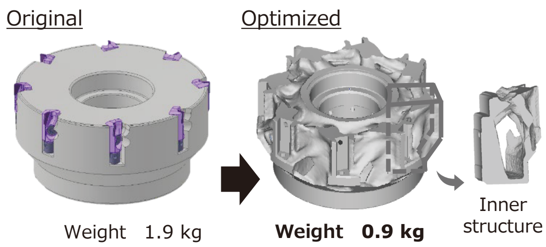


Fig. 4. Weight reduction results of the steel cutter body

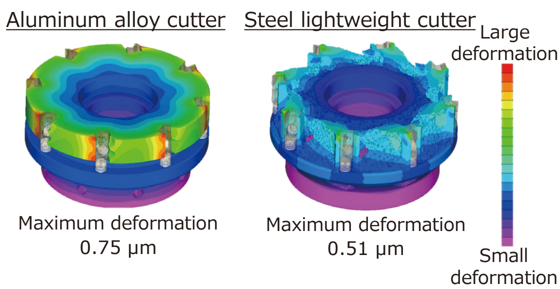


Fig. 5. Stress analysis results of the cutter bodies

Figure 6 shows the developed lightweight steel cutter. The body with complex internal structures was made using a 3D printer, followed by machining to finish the precision components. Front face milling tests were conducted under the machining conditions shown in Fig. 7, confirming that

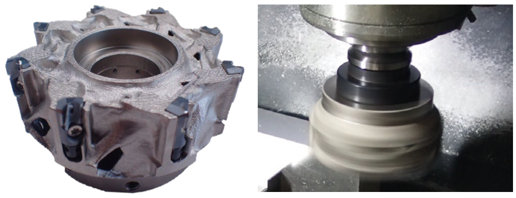


Fig. 6. Appearance of the developed product and the cutting process

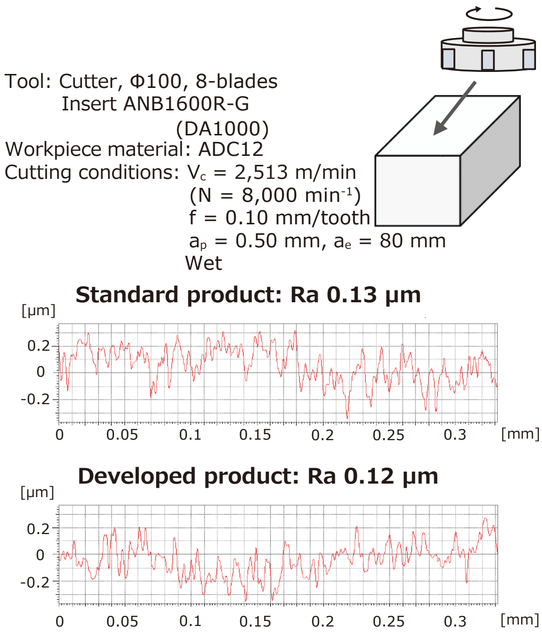


Fig. 7. Surface roughness in high-speed machining

the surface roughness of the machined parts was comparable to that achieved with the standard steel cutter.

We also conducted cutting tests at the client's facility, where multiple cutting passes with a small-diameter cutter were necessary due to the weight limitations of the machining center spindle. By using a large-diameter lightweight steel cutter, we achieved machining in a single pass, increasing efficiency by a factor of six or more, while maintaining the same machining accuracy.

4. Development of Long-Edge Cutter Body for Machining Difficult-to-Cut Materials

Unlike the aforementioned aluminum alloys, difficult-to-cut materials such as nickel-based alloys and titanium alloys generate a large amount of cutting heat during machining, so it is important to supply cutting fluid to the entire cutting edge.

The 63 mm-diameter long-edge cutter with multiple inserts shown in Fig. 8 is often used for vertical wall machining of difficult-to-cut materials. Conventional products typically have only one coolant channel directing fluid toward the rake face of each insert, primarily cooling the corner. This is because only straight channels can be fabricated using conventional processes. In addition, there is a difference in flow rates among the channels, which causes a variation in the life of each insert. Therefore, by utilizing AM, we have attempted to realize a long-edge cutter that can cool the entire cutting edge more uniformly.

Figure 9 shows a model of a long-edge cutter body modified to a 3D printer-specific design. The curved coolant channels deliver cutting fluids to five spots on each insert: three on the rake face and two on the flank face. The inside of the body is hollowed out exclusively for the cutting fluids, so that the fluids can be supplied evenly to all cutting edges. The chip pockets were minimized to the necessary size for vertical wall machining, which elimi-

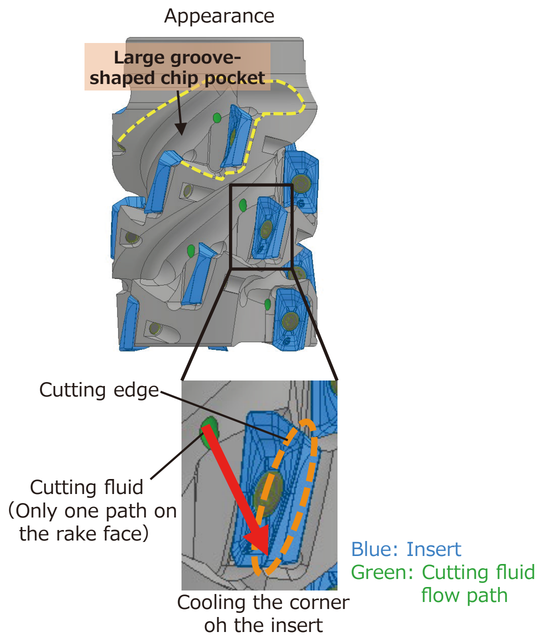


Fig. 8. Conventional product

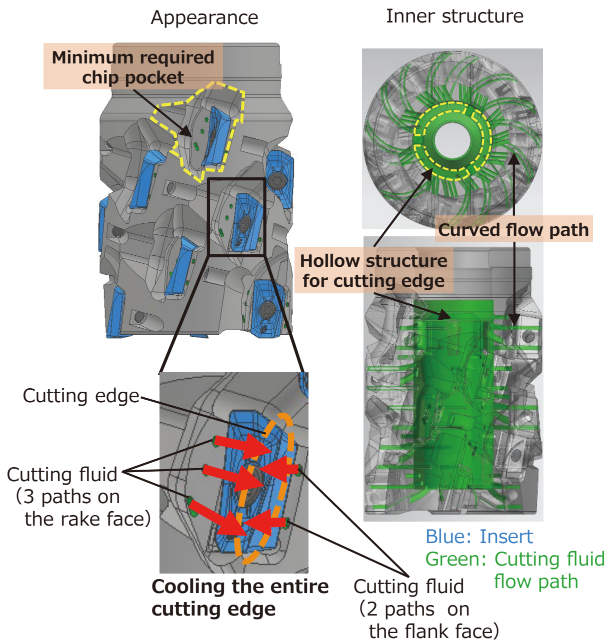


Fig. 9. Developed product

nated the need for supports during printing and increased rigidity by 1.2 times.

Figure 10 shows the developed long-edge cutter and the flow rate for each row. The flow rate was consistent across all rows of the cutter. A shoulder milling test was conducted on a titanium alloy under the machining conditions shown in Fig. 11. Adhesion and chipping were reduced compared to the conventional product, indicating that multiple coolant channels improved the cooling performance.

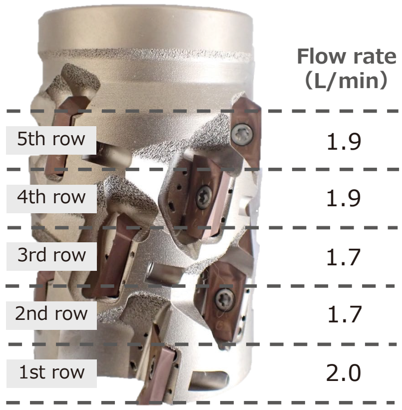


Fig. 10. Appearance of the developed product and results of the cutting fluid flow rate measurements

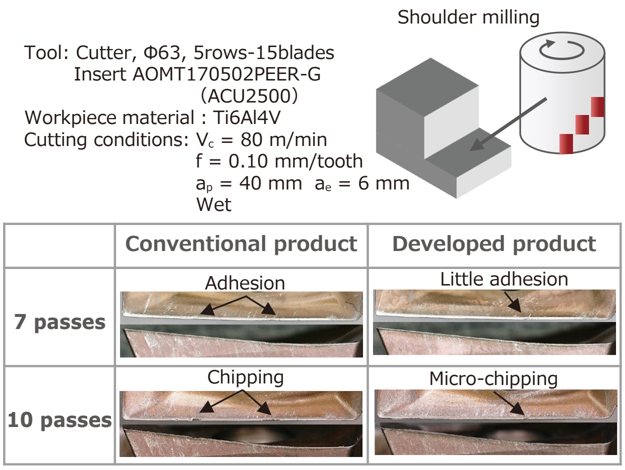


Fig. 11. Comparison of the tool damage in titanium alloy machining

5. Conclusion

We have developed a lightweight cutter body for aluminum machining and a long-edge cutter body for machining difficult-to-cut materials, each demonstrating the benefits of additively manufactured cutting tools.

In the automotive industry, it is expected that aluminum part machining will increase as electrification progresses in the near future. In particular, large-diameter lightweight cutting tools are desired for machining motor housings. Thus, we are also working on reducing the weight of cutting tools other than milling cutters by utilizing AM.

In the aircraft industry, the use of difficult-to-cut materials such as nickel-based heat-resistant alloys and titanium alloys is expected to increase in order to reduce engine noise and fuel consumption. We believe that optimizing coolant channels for more efficient cooling of cutting edges is crucial. By doing so, we aim to develop innovative cutting tools that achieve long tool life and high-efficiency machining.

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