Next-Generation Cemented Carbide for Machining Difficult-to-Cut Materials

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High-strength materials like titanium alloys and heat-resistant alloys are difficult-to-cut materials. They are used in industries such as aerospace and medical sectors, where the demand for high-quality processing and efficiency is increasing. For these demands, we have developed next-generation ultrafine-grained cemented carbide for difficult-to-cut materials. We successfully improved the interface strength between hard-phase particles to prevent damage from particle detachment and reduce wear in high-efficiency machining by enhancing the binder phase strength. By integrating these two technologies, we have achieved longer tool life in cutting difficult-to-cut materials.

Keywords: difficult-to-cut materials, titanium alloys, heat-resistant alloys, cemented carbides, cutting tools

1. Introduction

Heat-resistant alloys,*1 such as titanium alloys and Inconel, exhibit excellent corrosion resistance and mechanical properties, and have gained traction in the manufacture of aircraft engine components and medical implants. However, owing to their high strength and hardness, these alloys are prone to tool damage during machining. Furthermore, they are categorized as difficult-to-cut materials because their mechanical properties and low thermal conductivity cause cutting heat to concentrate at the cutting edge, thereby reducing tool life.[1]

In recent years, the projected growth of aerospace and medical sectors has increased the demand for improved surface quality and higher efficiency in cutting tools employed for machining difficult-to-cut materials.

To address these market demands, we have undertaken the research and development of specialized cutting tool materials tailored to the challenges posed by these alloys. This study introduces a novel cemented carbide,*2 developed based on the unique damage mechanisms encountered in the machining of difficult-to-cut materials.

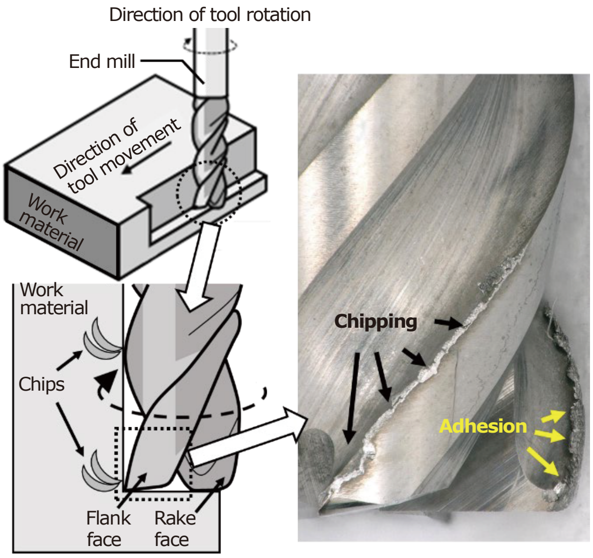


Fig. 1. Example of tool damage in end milling of difficult-to-cut metals

2. Issues in Machining Difficult-to-Cut Materials

2-1 Damage form of tools

The machining of difficult-to-cut materials is characterized by severe tool damage owing to the inherent properties of these materials. As these materials are expensive, extended tool life and stable performance are essential. Therefore, cemented carbide, which exhibits high hardness, heat resistance, and wear resistance, is typically employed for such applications, providing reliable performance under harsh machining conditions. Figure 1 illustrates typical damage to an end mill when machining difficult-to-cut metals. Owing to low thermal conductivity of the work material, cutting heat accumulates at the tool edge, resulting in adhesion*3 of the work material. This increases cutting resistance, eventually causing chipping*4 and accelerating tool damage, thereby shortening tool life.

2-2 Damage mechanism of cemented carbide

Cemented carbides consist of tungsten carbide (WC) as the hard phase and cobalt (Co) as the binder phase. Fine-grained cemented carbides, which predominantly contain submicron WC particles, are utilized for drills and end mills owing to their superior hardness and strength compared with typical cemented carbides. Figure 2 shows the damage process in cutting tools made from fine-grained cemented carbide. Initially, wear progresses from the cutting surface, and the binder phase, which exhibits lower hardness than the hard phase, is selectively worn away. Consequently, the WC particles detach owing to inadequate support from the binder phase, while the high cutting resistance triggers adhesion, resulting in significant chipping.

To mitigate this issue, we focused on strengthening the interface between the WC particles for reducing particle detachment, which is the primary cause of damage, thereby improving the strength of the binder phase to inhibit wear.

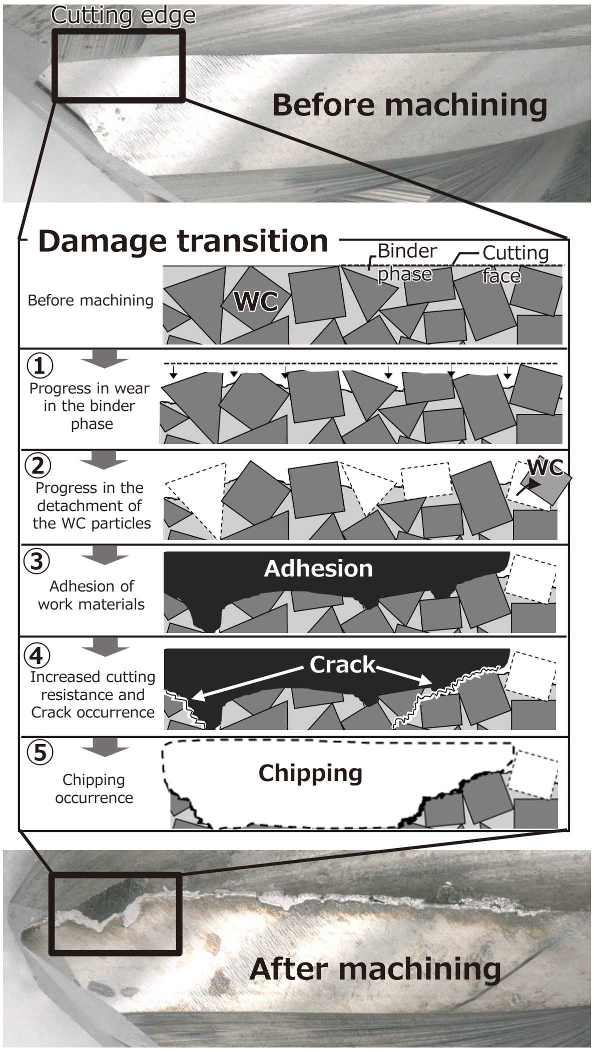


Fig. 2. Tool damage of difficult-to-cut materials

3. Enhancement of Interfaces Between Hard Phase

3-1 Investigation of the interface between WC particles in fine-grained cemented carbides

Scanning transmission electron microscopy energy dispersive X-ray spectroscopy (STEM-EDX) was employed to examine the contact surface between the WC particles in cemented carbide (WC-WC interface). Segregation of Co which serves as the binder phase and vanadium carbide (VC) was observed, as depicted in Fig. 3.

Uniform and fine microstructures are critical for fine-grained cemented carbides. Adding VC as a grain growth inhibitor during sintering is a typical method for improving microstructural uniformity. We speculate that the presence of VC influences the bonding strength between WC particles, indicating a need to improve the interface strength. However, fine-grained cemented carbides typically feature WC particles smaller than 1 µm; consequently, the WC-WC interface is equally small, making direct measurements of the interface strength particularly challenging. Therefore, we developed a novel method for measuring the interface strength.

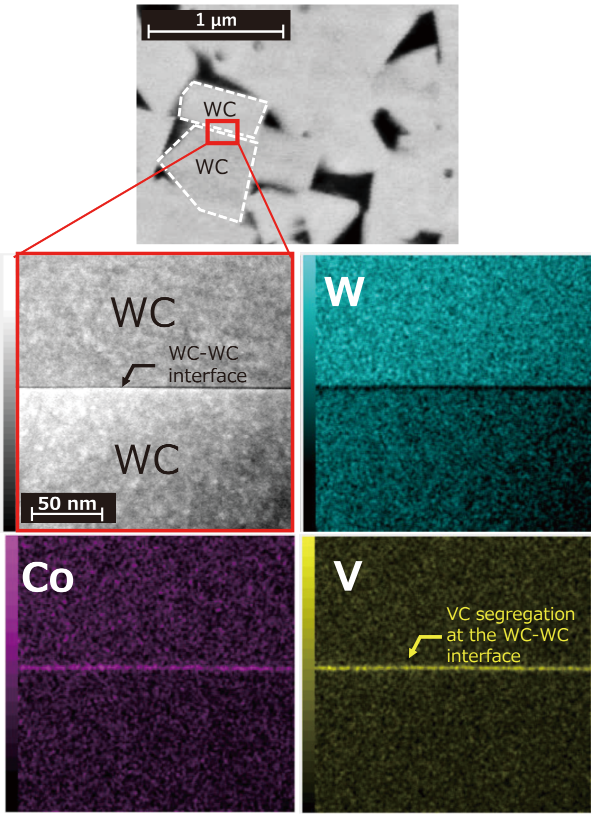


Fig. 3. STEM-EDX observation of WC-WC interface in fine-grained cemented carbide

3-2 Measurement of interface strength between WC particles

To measure the interface strength, we employed a cantilever test specifically designed to induce rupture at the WC-WC interface. Utilizing a cemented carbide with coarse WC particles (approximately 50 µm), a micro cantilever containing a single interface of WC-WC particle was fabricated via FIB,*[5] as shown in Fig. 4. A load was applied at the tips of the lever utilizing a nanoindenter,*[6] resulting in rupture at the WC-WC interface during a micro-bending test,*[7] thereby enabling direct measurement of the interface strength.

Figure 5 presents an example of the interface strength measurement results. The stress–strain curve, derived from the lever shape and breaking load, enabled the determination of breaking stress, which serves as a measure of the WC-WC interface strength. A comparison of the WC-WC interface strengths of cemented carbides with and without VC is shown in Fig. 6. The addition of VC to the cemented carbide decreased the WC-WC interface strength by approximately 20%. This result quantitatively demonstrates that VC segregation at the WC-WC interface significantly reduces the interface strength.[(2)]

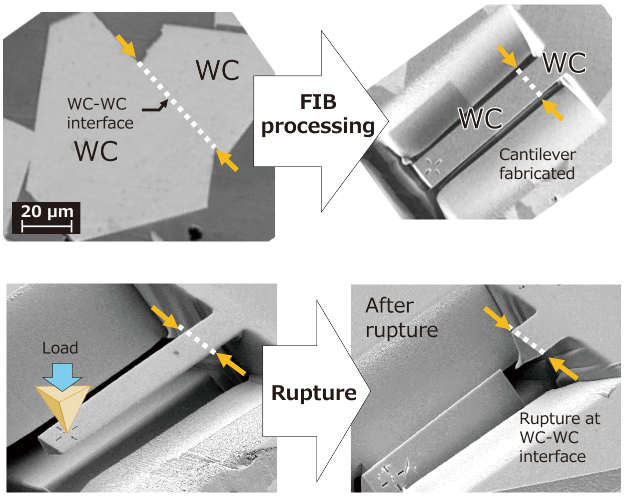


Fig. 4. Micro-bending test at the WC-WC interface

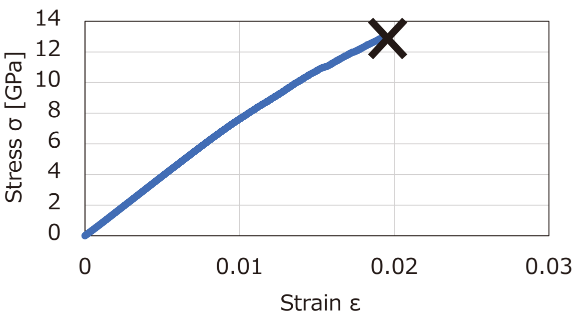


Fig. 5. Example of stress-strain curve obtained from the bending test

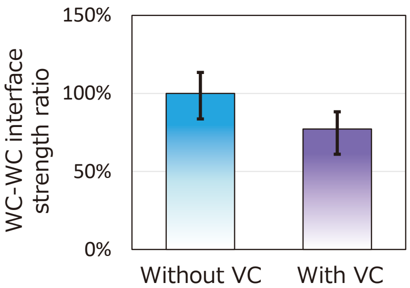


Fig. 6. Measurement results of the WC-WC interface strength in cemented carbide

3-3 Properties of cemented carbide with reinforced hard-phase particle interfaces

Because VC segregation at the WC-WC interface negatively impacts the interface strength, we investigated strategies to control the segregation. VC, which dissolves in the binder phase, acts on the surface of the WC particles as a grain growth inhibitor during sintering and solidification, resulting in segregation between the WC particles. To control the fine structure of the WC surfaces, we optimized the composition of the cemented carbide as well as the entire fabrication process, including raw powders, mixing, and sintering. Consequently, a new cemented carbide characterized by atomically controlled interfacial microstructures was developed. The strength of the WC-WC interface was enhanced by approximately 25% in the developed fine-grained cemented carbide, compared with the conventional cemented carbide containing VC, as shown in Fig. 7.

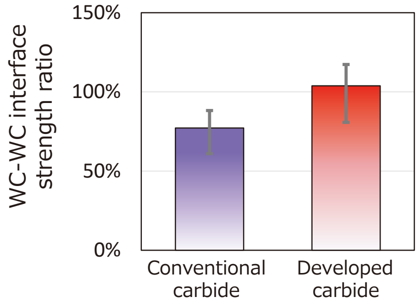


Fig. 7. Measurement results of the WC-WC interface strength in the developed cemented carbide

4. Reinforcement of Binder Phase

4-1 Challenges in high-efficiency machining

Figure 8 presents a typical example of damage to the cutting edge incurred during the machining of difficult-to-cut materials under high-efficiency conditions. Significant wear and adhesion were observed, which was attributed to the selective wear of the binder phase during the machining of the high-strength difficult-to-cut materials as well as the reduced hardness of the binder phase at elevated temperatures generated at the cutting edge during high-efficiency machining.(3)

To address these challenges, we developed a novel binder phase material that exhibits enhanced wear resistance, even under high-temperature and high-load conditions, making it suitable for high-efficiency machining.

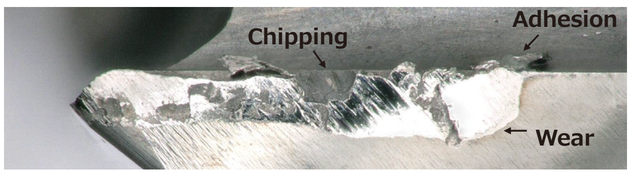


Fig. 8. Typical tool damage in high-efficiency machining of difficult-to-cut materials

4-2 Features of high-strength binder phase

To comprehensively analyze the physical properties of the developed binder phase, we measured the strength of the binder phase within the microstructure of the cemented carbide at both room and high temperatures employing a nanoindenter. As shown in Fig. 9, the hardness of the newly developed binder phase was 40% higher at room temperature and 6.1 times higher at 600°C than the conventional binder phase. This improvement in hardness prevents the softening of the binder phase caused by the cutting heat generated during the machining of difficult-to-cut materials, thereby significantly reducing wear.

Figure 10 shows the results of high-temperature compression tests comparing cemented carbides with the new binder phase and conventional cemented carbide. The compressive rupture strength of the newly developed cemented carbide was 10% higher than that of the conventional material at 600˚C. This increased strength prevents plastic deformation and chipping under high-load conditions, thereby ensuring excellent tool performance during high-efficiency machining.

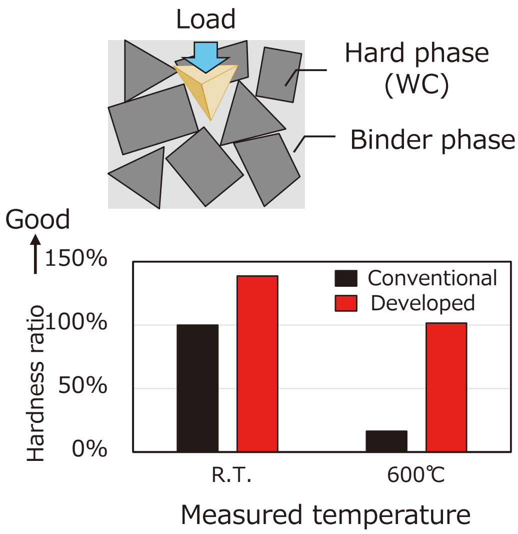


Fig. 9. Results of hardness measurement of binder phase

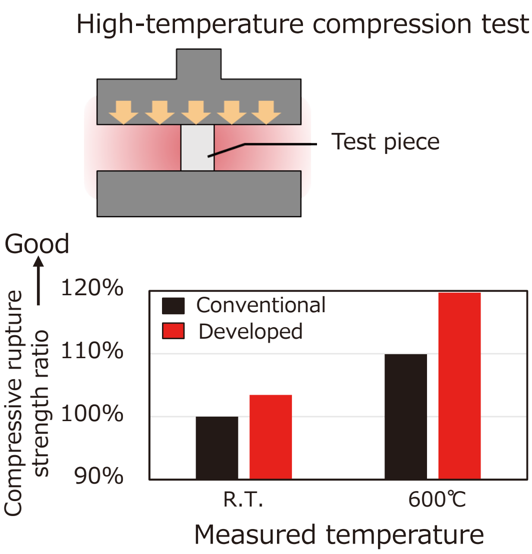


Fig. 10. High-temperature compressive test results

5. Performance of Cemented Carbides Suitable for Machining Difficult-to-Cut Materials

By integrating interfacial reinforcement between WC particles with binder phase strengthening techniques, we developed novel cemented carbides specifically designed for difficult-to-cut materials. Figure 11 illustrates the results of tool life evaluation during the end milling of the titanium alloy. The tool damage images indicate that although conventional cemented carbides exhibit adhesion and chipping, the newly developed material substantially reduces the damage and improves tool life by factor of two.

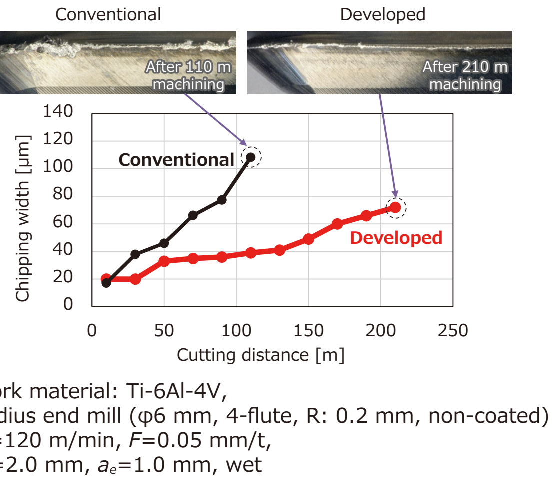


Fig. 11. Results of titanium alloy machining

The results of tool life evaluation under high-efficiency conditions during the end milling of Inconel are shown in Fig. 12. At a cutting speed of v_c = 30m/min, the developed cemented carbide demonstrated reduced wear and a 30% longer tool life than the conventional carbide. At a high cutting speed of v_c = 90 m/min, under high-efficiency machining conditions, the developed cemented carbide exhibited significantly less wear and a 40% longer

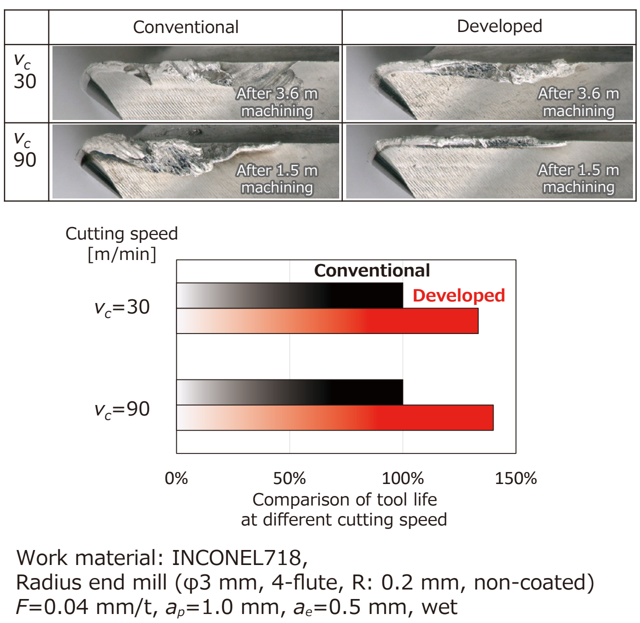
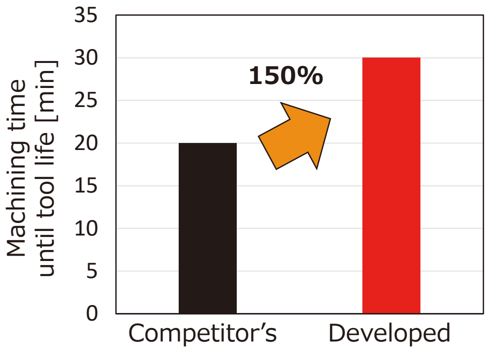


Fig. 12. Results of Inconel alloy machining

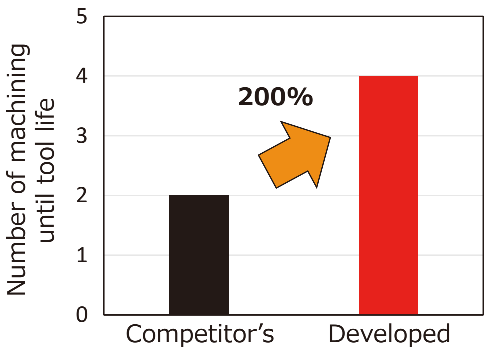
tool life.

The next-generation cemented carbide developed in this study exhibited longer tool life than conventional materials during the machining of titanium alloys and Inconel. Furthermore, it demonstrated exceptional performance under high-efficiency machining.

Figure 13 presents the customer evaluation results. Example (a) shows the results of end milling of titanium alloy, wherein the developed material reduced the chipping of the cutting edge and extended the tool life by 50% relative to competing materials. Example (b) presents results from Inconel end milling, demonstrating that the developed product doubled tool life compared with that of the competitor, significantly inhibiting edge loss and wear.



(a): Rough machining of block material (Ti-6Al-4V)
Square end mill (φ6 mm)



(b): Rough machining of airplane engine components (INCONEL 718 [AG])
Square end mill (φ8 mm)

Fig. 13. Evaluation results in customers

6. Conclusion

Techniques to enhance the interface strength between WC particles in cemented carbides and improve the high-temperature properties of the binder phase has been developed and successfully applied to fine-grained cemented carbides. Tools utilizing the developed fine-grained carbide exhibited extended tool life and facilitated the high-efficiency machining of difficult-to-cut materials, including titanium alloys and Inconel. These techniques are anticipated to serve as fundamental technologies applicable to both difficult-to-cut materials as well as the typical cemented carbides. We believe that these advancements will significantly contribute to enhanced manufacturing efficiency and reducing costs for customers by ensuring stable surface quality, improving machining efficiency, and extending tool life.

Technical Terms

*1 Heat-resistant alloy: An alloy exhibiting excellent corrosion resistance, oxidation resistance, and strength in high-temperature environments exceeding 1000˚C. These materials are typically used in jet engines and gas turbines.

*2 Cemented carbide: Composite ceramic and metal materials primarily consisting of tungsten carbide (WC) as the hard phase and cobalt (Co) as the binder phase.

*3 Adhesion: The phenomenon where the work material melts due to the cutting heat generated at the cutting tool edge, causing it to adhere to the cutting tool. Increased deposition reduces machining accuracy and shortens tool life, necessitating frequent tool replacement.

*4 Chipping: A formation of minute chips or fragments on the cutting edge of a tool, typically caused by mechanical stress during the cutting process.

*5 FIB: Focused Ion Beam (FIB) technique involves irradiating a sample with an ion beam to perform microscopic processing.

*6 Nanoindenter: Device that applies minimal loads to measure the hardness and modulus of elasticity of materials at the nanoscale.

*7 Bending test: A test was conducted to assess the fracture resistance of a material against bending by applying a force to the test piece and measuring the load at the time of fracture.

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