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Experimental Investigation on the Mechanism of Cutting Performance Enhancement of YG8N Cemented Carbide Tools with Tesla-Valve-Inspired Micro-Textures under MoS_2-Based Minimum Quantity Lubrication

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Abstract

To improve the wear resistance, heat dissipation and anti-adhesion capability of cemented carbide tools in machining titanium alloys, Tesla-valve-inspired anisotropic micro-textures were fabricated on the rake face of YG8N cemented carbide tools using femtosecond laser processing. Cutting experiments were carried out under MoS_2-based hybrid minimum-quantity lubrication (MQL). A tri-axial piezoelectric dynamometer, temperature sensors and surface characterization techniques were employed to systematically compare non-textured tools, forward-textured tools and reverse-textured tools at low (300 mm/s) and high (1000 mm/s) cutting speeds in terms of cutting force, friction coefficient, temperature distribution, tool wear and chip morphology. The results show that: the micro-textures significantly reduce the actual contact area between the tool and the workpiece and enhance both the storage and transport of cutting fluid, thereby improving lubrication and cooling conditions; at high cutting speeds, the forward-textured tool achieves reductions of about 28.1% in cutting force and 50% in friction coefficient compared with the non-textured tool, lowers the tool-tip temperature by roughly 50% and decreases the wear-band width by about 70%; the micro-textures promote chip curling and evacuation, suppressing the formation of built-up edge and adhesion layers and thus markedly extending tool life. This study elucidates the synergistic mechanism of lubrication and heat dissipation by Tesla-valve-inspired micro-textures in enhancing cutting performance, and provides both theoretical and experimental support for the design of high-performance cemented carbide cutting tools.

Keywords

Tesla-valve micro-texture; YG8N cemented carbide; MoS_2 nanofluid; minimum-quantity lubrication; cutting performance

1. Introduction

Cemented carbides play a critical role in cutting tools due to their excellent hardness, wear resistance, and thermal stability. However, during the machining of titanium alloys, their poor thermal conductivity and high chemical reactivity often lead to localized high temperatures and adhesive wear. These phenomena not only accelerate tool wear but also degrade the surface quality of the machined parts, ultimately reducing machining efficiency[1].

In recent years, surface engineering has emerged as an effective approach to enhance tool performance. Numerous studies have demonstrated that micro-texturing the tool surface can effectively trap chips, improve the frictional interaction between the tool and workpiece/chip, and prolong tool life. Pang et al.[2] designed symmetrical conical micro-textures on the tool surface, where the lubricant stored within the textures forms a protective film during cutting, resulting in a significantly lower friction coefficient compared to untextured tools. Microtextured tools can effectively mitigate wear, thermal damage, and built-up edge formation during cutting. Wang et al.[3] reported that incorporating groove-like micro-textures on the tool surface can substantially reduce the impact of cutting temperature on performance. The textured tools exhibited a 40–50% reduction in cutting forces, a significant decrease in built-up edge formation, and a 69.6% increase in tool life. Similarly, Gong et al.[4] conducted cutting experiments comparing microtextured and untextured tools. Their results showed that microtextured tools outperform untextured ones in terms of material removal rate and heat reduction, achieving a 15.3% decrease in tangential cutting force and a 12.2% reduction in cutting temperature, demonstrating excellent wear resistance.

As a widely studied non-mechanical pump technology, the Tesla valve has shown unique advantages in surface engineering. Against this backdrop, this study employs femtosecond laser processing to fabricate Tesla valve micro-textures on YG8N cemented carbide surfaces, and investigates their effects on cutting performance.

2. Mechanism of Micro-texture Function

In this study, different types of microtextured tools were designed based on the anisotropic characteristics of the Tesla valve, as illustrated in Figure 1. The Tesla valve exhibits a unique diode-like behavior, and its working principle is as follows. As shown in Figure 1a, when fluid flows forward through the Tesla valve micro-texture, most of the fluid bypasses the curved channels and flows along the main channel with relatively low resistance. In contrast, Figure 1b shows that when the fluid flows in the reverse direction, a blocking effect occurs at the intersection of the straight and curved channels. After partial diversion, a larger portion of the fluid enters the curved channels and collides with the main channel flow, resulting in increased flow resistance. Based on this principle, applying Tesla valve micro-textures to the tool surface can reduce tool wear during cutting while simultaneously enhancing the dissipation of cutting-generated heat[5].

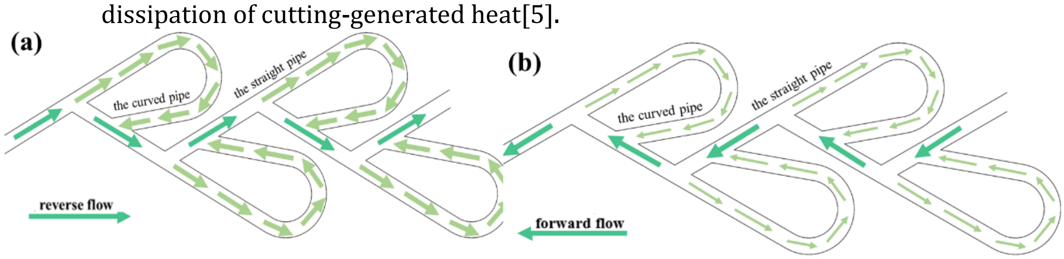

Fig 1. The Working Principle of the Tesla Valve

Figure 2 illustrates the cutting schematic under the condition of cutting fluid. Regions I, II, and III represent the elastoplastic deformation zones of the workpiece caused by tool compression. The cutting zone can be divided into two parts: A, the cutting fluid injection region, and B, the chip flow region. The cutting fluid is ejected from the nozzle and flows in the direction indicated by the arrows in region A. As the fluid is expelled at high speed, it forms a continuous hydrodynamic jet that collides with the cemented carbide tool, causing a deflection in the fluid flow and directing it along the tool surface. Continuous fluid flow carries away the heat generated during cutting, reducing the cutting temperature, mitigating thermal softening, and decreasing the formation of built-up edge. Region B corresponds to the tool micro-texture area. Under the instantaneous high temperature and pressure during cutting, the workpiece is prone to thermal softening. The micro-textures can better retain the cutting fluid, which reduces adhesion on the rake face and improves overall tool performance.

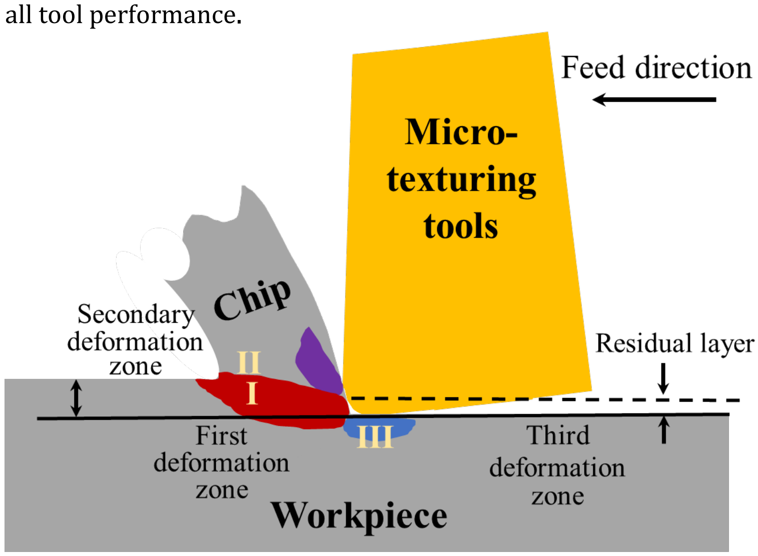

Fig 2. Schematic diagram of turning under cutting fluid conditions

3. Fabrication of Micro-textures and Cutting Parameter Setup

A HR-Femto-50 femtosecond laser was used to fabricate Tesla valve micro-textures with different orientations on the rake face of YG8N carbide tools. The laser processing parameters were set as follows: laser power of 28 W, central wavelength of

1035 nm, repetition rate of 20 kHz, pulse width of 350 fs, and scanning speed of 100 mm/s. The resulting Tesla valve micro-textures had a width of 62.6 μm and a depth of 40.4 μm. The geometric parameters of the YG8N tool and the surface micro-textures are shown in Figure 3.

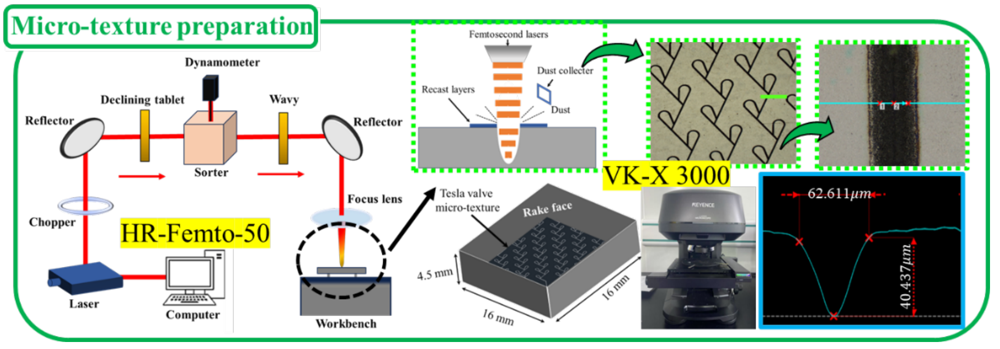

Fig 3. Laser processing process and texture size

Cutting experiments were conducted on YG8N carbide tools using an SLD 90 CNC lathe. As shown in Figure 4, the workpiece was a TC4 titanium alloy rod with a length of 300 mm and a diameter of 100 mm. The rod was mounted on the lathe chuck, while the tool was installed on the tool holder. A temperature sensor was fixed near the tool tip to monitor the cutting temperature. Cutting forces were measured using a YDC-III 89A piezoelectric turning dynamometer and a charge amplifier. The cutting parameters are listed in Table 1. After cutting, the surface roughness and integrity of the carbide tool were examined using a VK-X 3000 series confocal microscope. A CARL ZEISS Sigma 300 SEM was used to observe wear on the tool and chips, while energy-dispersive X-ray spectroscopy (EDS) was employed to analyze the chemical composition of the tool surface.

Tab 1. Cutting parameters of the tool

rake angle $\gamma(^\circ)$	Cutting speed n(r/min)	Cutting depth a_P(mm)	Feed rate (mm/r)	Cutting time t(s)
10	100/250	0.3	0.2	600

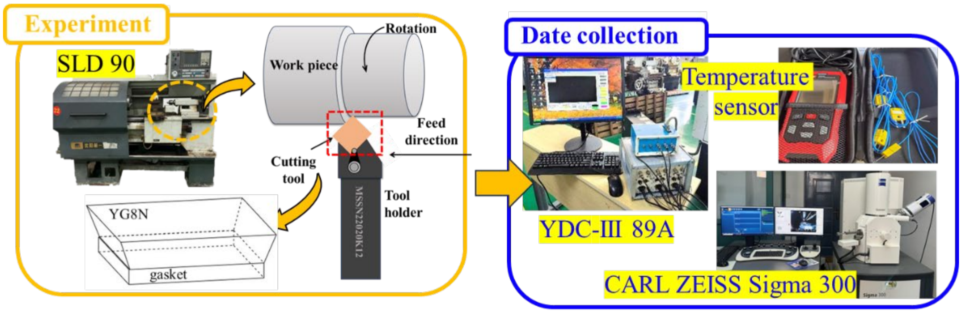

Fig 4. Tool holder with sensor tool

Viscosity is a key parameter for evaluating a fluid's resistance to shear deformation, and it is influenced by intermolecular forces and temperature variations. During the cutting process, an appropriate viscosity helps maintain the stability of the lubricating oil film, thereby reducing friction and wear between the tool and the workpiece, as well as between the tool and the chips. However, heat accumulation during the cutting process can lead to localized temperature rises, altering the viscosity characteristics of the cutting fluid and affecting its lubrication and cooling performance. To investigate the effect of temperature on cutting fluid viscosity, experiments were conducted to measure the viscosity of the base oil and 1.5% MoS_2 nanofluid at 40, 50, 60, 70, and 80 °C, as shown in Figure 5. The results show that the viscosity of the cutting fluid decreases with increasing temperature, consistent with the Arrhenius equation describing the viscosity–temperature relationship[6]. According to the experimental data, at 80 °C, the viscosity of the base oil was 11.1 mPa·s, while that of the MoS_2 nanofluid was 15.6 mPa·s—representing a 40.5% increase over the base oil. This difference is primarily attributed to the layered structure of MoS_2. The addition of dispersants helps minimize the disruption of interlayer van der Waals forces caused by shear stress, thereby reducing the fluid's shear resistance and forming a more stable nanofluid system. Moreover, MoS_2 is considered an environmentally friendly lubricant. Based on these advantages, MoS_2 cutting fluid was selected for the subsequent machining experiments. Its microstructure is shown in Figure 6.

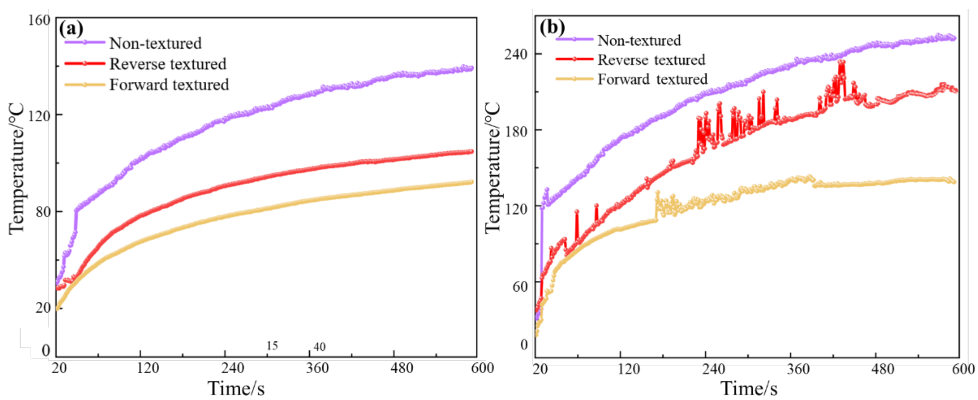

Fig 5. Variation of cutting fluid viscosity at different temperatures

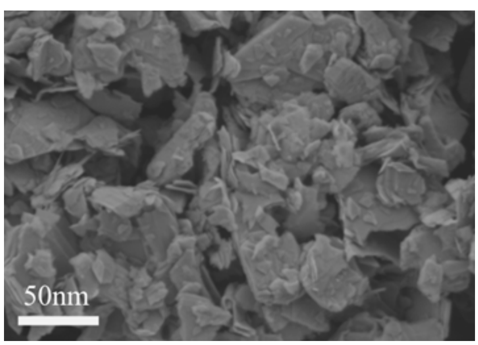

Fig 6. SEM morphology of MoS_2

Based on the results of friction and wear tests, cutting experiments were conducted at two different cutting speeds (300 mm/s and 1000 mm/s). A 1.5% minimum quantity lubrication (MQL) condition was applied, using a mixture of PAO 6 base oil, dispersant, and MoS_2. The feed rate was maintained at 0.2 mm/rev and the depth of cut at 0.3 mm throughout the experiments. Each test was repeated three times, and the average value of the results was used for analysis.

4. Results and Analysis

4.1. Cutting Force

Cutting force is a key indicator of tool performance. During the cutting process, the presence of microtextures alters the actual contact area between the tool and the chip. Using a three-axis piezoelectric dynamometer to acquire data, the average cutting forces of YG8N cemented carbide tools at different cutting speeds were obtained through numerical calculations. The friction coefficient (COF) at the tool–chip interface was then calculated according to Equation (1).

$$\mu = \tan\left(\gamma_0 + arc\tan\frac{F_p}{F_c}\right) \quad (1)$$

Where F_p is the radial force (N), F_c is the tangential force (N), and γ_0 is the rake angle of the tool (°).

Figure 7 shows the average cutting force and coefficient of friction (COF) for different tools at varying cutting speeds. Under low-speed cutting conditions, the average tangential forces F_c for the non-textured, forward-textured, and reverse-textured tools were 590.7 N, 510.3 N, and 498.7 N, respectively. Compared to the non-textured tool, the forward and reverse micro-textured tools reduced the tangential force by approximately 13.7% and 14.6%, respectively.

Under high-speed cutting conditions, the cutting forces for all types of tools show a decreasing trend. The non-textured tool still exhibits the highest tangential force at 454.4 N, while the forward-textured and reverse-textured tools reduce the force to 410.9 N and 420.7 N, respectively. The coefficient of friction (COF) for the forward-textured tool is 0.684, representing a reduction of approximately 28.1% and 11.6% compared to the non-textured (0.95) and reverse-textured (0.84) tools, respectively. The results indicate that in a high-speed shear flow field, the forward-oriented micro-texture significantly enhances the flow velocity of the cutting fluid within the grooves. Compared to low-speed conditions, this facilitates faster chip removal and more efficient heat dissipation, demonstrating superior friction-reducing and cooling performance. Additionally, the micro-texture structures can trap chips during the cutting process and, under the action of shear and friction forces, compress and drag them into the contact interface. This transforms the friction mode from pure sliding to a combined sliding–rolling friction, thereby effectively improving tribological performance[7]. The introduction of micro-textures on the tool surface alters the distribution of cutting forces, alleviating local stress concentrations at the tool–workpiece interface. This effect is further validated through detailed simulations. Moreover, the reduction in cutting stress helps suppress plastic deformation in the workpiece. During machining, high-stress regions are primarily concentrated in the shear zone near the main cutting edge. The micro-textures facilitate the removal of stored chips along with the lubricant by providing alternative flow paths. High-speed cutting leads to reduced plastic deformation and lower cutting forces, allowing nanoparticles to more easily penetrate the friction interface, thereby enhancing lubrication and cooling performance and further reducing the coefficient of friction.

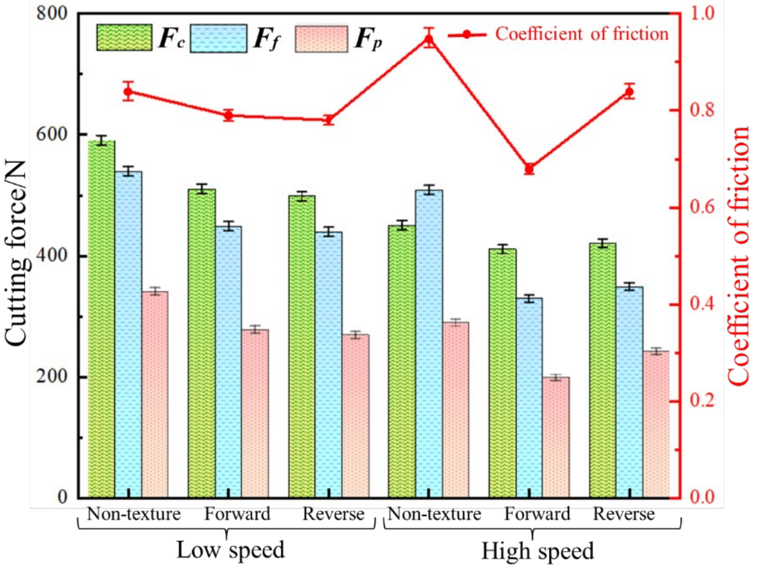

Fig 7. Cutting forces and friction coefficients of different cutting tools

4.2. Cutting temperature

During the cutting process, a portion of the heat is conducted into the interior of the tool and subsequently transferred to components such as the insert, shim, and tool holder through contact conduction. Since titanium alloy has a much lower thermal conductivity than the carbide tool, some of the heat is removed by the cutting fluid, while the majority is carried away by the chips, as illustrated in Figure 8. Additionally, contact between the tool components and the surrounding air enhances convective heat transfer, further influencing the overall thermal distribution.

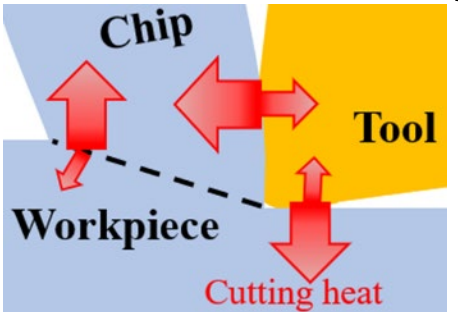

Fig 8. Generating and transmitting cutting heat during the cutting process

Figure 9 shows the temperature variations over 10 minutes under both low-speed and high-speed cutting conditions for different tool types. The experimental results indicate that, in both scenarios, the cutting temperature follows the order: non-textured tool > reverse-textured tool > forward-textured tool. This suggests that micro-textures play a positive role in reducing cutting temperatures. Under low-speed cutting conditions, the temperature of the non-textured tool rose rapidly to 80 °C within 40 seconds and peaked at 142 °C. In contrast, the temperature rise of the textured tools was more gradual. The reverse-textured tool reached a maximum cutting temperature of 100 °C, while the forward-textured tool peaked at only 80 °C, indicating that textured tools play a significant role in slowing down temperature increases during cutting. This difference is primarily attributed to the role of micro-textures in enhancing lubrication, cooling, and heat conduction. During cutting, the majority of heat is carried away by the chips, while the remaining heat must be dissipated through cooling by the cutting fluid in the cutting zone. Non-textured tools lack microstructures that can retain lubricants, resulting in a larger contact area between the tool and the workpiece. The increased friction hinders effective heat dissipation, causing greater heat accumulation. This is the main reason why non-textured tools exhibit higher cutting temperatures[8].

In contrast, during high-speed cutting, the increased cutting velocity intensifies the rate of plastic deformation. At the same time, the rapid cutting and friction generate more heat, leading to a general rise in temperature for all tools. Among them, the non-textured tool exhibits the highest temperature at 270 °C, while the cutting temperatures for the forward- and reverse-textured tools are reduced to 135 °C and 220 °C, respectively. Compared to the non-textured tool, the forward-textured tool shows a temperature reduction of approximately 50%, and about 18.5% lower than the reverse-textured tool. The experimental results indicate that, relative to the non-textured tool, textured tools allow the cutting fluid to flow more easily through the cutting zone, thereby carrying away more heat. Meanwhile, the micro-textures also effectively enhance convective heat transfer with the surrounding air, demonstrating excellent thermal dissipation performance under various cutting conditions. Due to the thermo-fluid coupling effect, a heat-induced fluid lubrication film may form at the tool–chip interface during cutting, which helps reduce local shear stress and interfacial friction, thereby improving overall cutting performance.

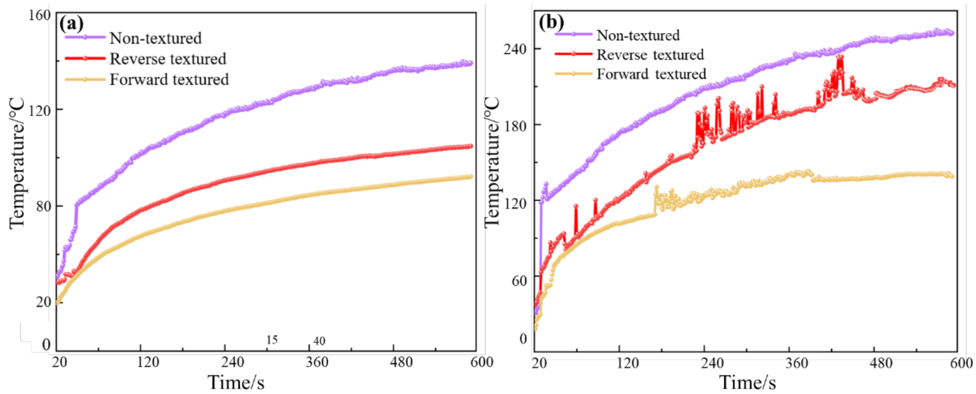

Fig 9. Cutting temperatures of different tools (a) Low speed conditions (b) High speed conditions

5. Conclusions

By fabricating Tesla-valve-inspired micro-textures on the rake face of YG8N cemented carbide tools and conducting cutting tests under MoS_2-based hybrid MQL conditions, the mechanism of cutting-performance enhancement was systematically revealed:

(1) Pronounced texture-orientation effect. Under low-speed conditions, both forward and reverse textures reduce cutting force and temperature rise; under high-speed conditions, the forward texture delivers the greatest improvements in cutting force, friction coefficient and temperature, exhibiting superior cooling and anti-friction characteristics.

(2) Synergistic lubrication and heat dissipation. The micro-textures decrease the actual tool–chip contact area, alter chip flow paths and store cutting fluid, thereby stabilising the lubricant film and enhancing convective heat transfer. Tool-tip temperatures are up to 50% lower than those of non-textured tools.

(3) Marked suppression of wear and adhesion. The micro-textures collect debris and alleviate stress concentration, restraining the formation of adhesion layers and built-up edge. Wear-band width is greatly reduced and tool life is significantly extended.

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