Effect of volcano-like textured coated tools on machining of Ti6Al4V: an experimental and simulative investigation

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Abstract
The present study was to reduce the adhesion and wear that happened on the rake face during machining of Ti6Al4V alloys by employing volcano-like textured coated tools. A combination of experimental and simulative investigation was adopted. DEFORM-3D software with updated Lagrangian formulation was used for numerical simulation, and the thermo-mechanical analysis was performed using Johnson–Cook material model to predict the cutting forces, cutting temperature, chip morphology, and tool wear. In cutting experiments, volcano-like textures with different area densities (10%, 20%, 30%) were fabricated by fiber laser on the rake face of cemented carbide tools close to the main cutting edge. Then, these textured tools were deposited with CrAlN coating through cathodic vacuum arc ion plating technique. Experiments in cutting Ti6Al4V alloys were carried out with the textured coated tools and non-textured coated tool under dry and wet cutting conditions. Then, cutting forces, chip morphology, and tool wear were investigated. The results showed that textured coated tools were superior to the conventional tool. Especially in wet cutting, the main cutting force and radial force of the coated tool with texture area density of 20% (VCT2) were reduced by 11.6% and 21.25%, respectively. Surface morphology of VCT2 tool had lower workpiece adhesion on the rake face. Therefore, VCT2 tool showed a better cutting performance. Finally, the mechanisms of textured coated tools under wet cutting conditions were proposed.

Keywords FEM modeling · Ti6Al4V · Volcano-like textures · Chip morphology · Tool wear

1 Introduction

Ti6Al4V alloys have become crucial materials for aerospace, shipbuilding, and chemical industries. The increasing demands for Ti6Al4V alloys are due to their excellent intrinsic properties, such as low density, high strength, and corrosion resistance. Nevertheless, these factors lead to poor machinability of Ti6Al4V alloys because of its small elastic modulus, high chemical reaction activity, and low thermal conductivity [1]. A lot of heat generated is confined over the tool-chip contact interface during the machining process, which results in high cutting temperature that in turn facilitates the chip adhesion on the rake face of cutting tools. In addition, high contact stress on the tool-chip contact interface in cutting of Ti6Al4V alloys makes adhesive wear more likely to appear, which shortens the tool’s life.

Laser surface texturing (LST) contributes to the improvement of tribological properties between contact surfaces, and it has been successfully used in various mechanical systems, such as bearings [2], mechanical seals [3], and cylinder liners [4]. Attempts at extending this concept to cutting tool may be also a promising method to improve the cutting performance. The advantages of surface texturing in anti-adhesion and friction-reduction are mainly attributed to several mechanisms such as reducing the contact area [5, 6], trapping wear debris [7], and retaining cutting fluids [8]. Machado et al. [9] reviewed the research progress of textured tools from 2016 to date and related preparation technologies. The summary of previous works showed that the concave textures (mainly including pits and linear grooves) played a significant role in improving the cutting forces, cutting temperature, tool life, and cutting quality of workpiece. The properties of micro-textured tools predominantly depend on its topography on the surface. Therefore, many scholars attempted at designing and fabricating various functional microstructures on the tool surface. Darshan et al. [10] fabricated pitted textures on the surface of a cemented carbide tool.
A (WC/Co) tool using a diode-pumped fiber. The textured tool reduced the contact area during the cutting process and enhanced the effectiveness of heat transfer compared with that of non-textured tool, which significantly restrained the cutting forces, cutting temperature, and tool surface wear. Mishra et al. [11] studied the effect of varied shapes and area densities of chevron textures on tool performance of cutting titanium alloys. A combination of three-dimensional simulation and cutting experiments was performed, and it suggested that the cutting forces were sensitive to the texture area density. Further, the authors established the linear regression model for tool-chip contact length and found the reduction of tool-chip contact length was an important mechanism for better effectiveness of textured tools.

However, investigations about the convex textures have shown a better anti-adhesion effect comparing to the concave textures [12]. Convex textures mainly incorporate the volcano-like, spherical crown, and W-shaped textures, which are composite textures with concave and convex morphology. Kang et al. [13] reported the volcano-like textured tools could reduce cutting forces and adhesion. To further understand the mechanisms of convex texture, Ma et al. [14] combined simulation and experiments to investigate the effects of different texture parameters (width, depth, and distance from the cutting edge) on the machining performance of the tools. Results proved that the micro-bump textured tools can decrease the tool-chip contact length, resulting in the reduction of forces as well as machining energy consumption compared with non-textured tool. Yu et al. [15] conducted a two-dimensional simulation about the cutting process of volcano-like textured tool under the conditions of cutting fluid lubrication. This work revealed the cutting mechanisms of textured tools under the wet conditions and solved the problem of tool weakness. Through the analyses above literatures, the introduction of convex texture reduced the adhesion and wear, which greatly extended the service life of the tool. However, defects also are existed on the textured tool. Once the textures are filled or destroyed, the anti-adhesion effect of the textured tool will be invalid. Commonly known protective coating is an indispensable component of high-performance cutting tools [16]. Hard coating, such as CrAlN and TiAlN, is deposited on the surface of the tool to ensure the wear resistance and high temperature resistance, which has been highly recognized in manufacturing industry [17]. Thus, hard coating can also be used to protect the textured surface of the tool. Zhang et al. [18–20] have been committed to investigating the combination of texture technology and coating technology for many years, and they comprehensively evaluated the cutting performance of the textured coated tools and found textures lead to a significant enhancement in the cutting performance compared with the conventional tool. Further, the synergistic effects of textured coated tools were proposed by the machining processes and scratch experiments. Textures can reduce the residual stress in the coating preparation. Meanwhile, hard coating also protected the surface morphology of the textures, which helped the improvement in surface wear and the service life of the tool.

Thus, we intended to explore the effect of the combination of volcano-like texture and hard coating on the cutting performance of the tool. Experimental and simulative investigation was carried out. Firstly, volcano-like textures were designed on the rake face of cemented carbide tools. DEFORM-3D was selected to simulate the cutting of Ti6Al4V alloys using volcano-like textured and non-textured coated tools. Then cutting experiments were conducted to validate the FEM model under different texture densities, cutting speeds, and cooling conditions. The cutting performance of different kinds of textured coated tools was evaluated. Finally, the mechanisms of the cutting performance of textured coated tools were to be discussed, which will contribute to the design and manufacturing methods of textures on the tool surface.

2 Simulation of the machining process

2.1 Finite element mode for machining

DEFORM-3D was selected to simulate the machining process based on updated Lagrangian formulation with cemented carbide cutting tool. The cutting performance of four kinds of tools was explored at different cutting speeds. The 3D FEM cutting model of tool and workpiece for simulation is exhibited in Fig. 1.

Fig. 1 The finite element modeling of cutting tool and workpiece
Non-textured tool and volcano-like textured tools were designed with SolidWorks based on the real shape and size of cutting tool and then imported into DEFORM-3D. After that, all cutting tools were endowed with CrAlN hard coating. The cutting tools and workpiece were meshed and ranged from 183,516 to 202,000 and 41,515 elements by adaptive meshing technique that ensured the accuracy of simulation model. To simplify nomenclature, the designed tool which was coated CrAlN without textures was named NCT. The designed tool which was coated CrAlN with volcano-like textures was denoted as VCT, and different texture densities (10%, 20%, 30%) were named as VCT1, VCT2, and VCT3, respectively. The three-dimensional shape and related parameters of the four tools are shown in Fig. 2 and Table 1.

2.2 J–C model for workpiece material

Ti6Al4V alloys were selected as the workpiece material. For finer mesh density, workpiece was represented as a curved model with a radius of 60 mm and curvature angle of 20°. There are a variety of constitutive equations describing material properties in DEFORM-3D, such as Johnson–Cook constitutive model, Zerilli-Armstrong constitutive model, and Bodner-Partom constitutive model. Johnson–Cook constitutive model can better reflect the strain hardening, strengthening, and thermal softening effects of the workpiece material, which is more in consistent with the actual cutting process. Empirical formula of the model can be written as:

\[
\bar{\sigma} = \left[ A + B \left( \frac{\dot{e}}{\dot{e}_0} \right)^n \right] \left[ 1 + C \ln \left( \frac{\dot{e}}{\dot{e}_0} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right] \tag{1}
\]

where \( \bar{\sigma} \) is the equivalent stress; \( A, B, and C \) are material yield stress, hardening modulus, and strain rate coefficient, respectively; \( n \) is hardening exponent and \( m \) is thermal softening coefficient; and \( T_r, T_m, \) and \( T \) represent room temperature, melting temperature, and operating temperature, respectively. \( \dot{e} \) is the effective plastic strain rate and \( \dot{e}_0 \) is the reference strain rate. The mechanical properties and constitutive model parameters for Ti6Al4V are listed in Table 2 [21, 22].

3 Experimental details

The cutting experiments were carried out with Ti6Al4V alloys in the form of a round bar with a radius of 30 mm and length of 100 mm selecting cemented carbide (TNMA160404, Toshiba Co., Ltd., Japan). Volcano-like textures were fabricated on the tool rake face by Raycus RFL C500 fiber laser (1080 nm wavelength, 500 W) with the processing parameters as described in Table 3. During the laser

### Table 1 Parameters of surface texturing

| Types | Diameter \( d \) (μm) | Height \( h \) (μm) | Space \( s \) (μm) | Area density \( \rho \) (%) | CrAlN coating thickness (μm) |
|-------|------------------|------------------|------------------|-----------------|------------------|
| NCT   | -                | -                | -                | -               | 2.5               |
| VCT1  | 120              | 8                | 336              | 10              | 2.5               |
| VCT2  | 120              | 8                | 238              | 20              | 2.5               |
| VCT3  | 120              | 8                | 194              | 30              | 2.5               |

\( \rho = \pi d^2 / 4s^2 \)
re-melting process, a laser with high energy and long pulse width was injected into the local zone of the tool. Driven by the gradient surface tension and the flow of local molten pool generated by laser radiation, a composite morphology with a certain height of raised edge bulge and central pit, volcano-like texture, was obtained [23, 24].

After laser irradiation, a layer of 2.5 μm CrAlN hard coating was deposited on the surface of textured tools using the vacuum cathodic arc ion plating technique. Prior to CrAlN deposition, these fabricated tools were cleaned in an ultrasonic cleaning machine for 18 min and dried in a pre-vacuum dryer for 15 min. CrAlN coating was prepared on a plasma and vacuum technology coating machine with target materials of Cr and Al. The coating deposition parameters were as follows: vacuum pressure of 0.2 Pa, bias voltage of −100–150 V, temperature of 420 °C, reaction gas of N2, and coating time of 160 min. The protection gas was Ar. After annealing treatment for 2 h at 180 °C, the required samples were obtained. The surfaces of these tools were measured using an upright optical microscope (Leica DM750) and an ultra-depth-of-field electron microscope (VHX-2000C). Figure 3 shows the four types of coated tools and morphology of the volcano-like texture.

Machining experiments were conducted on an engine lathe (CS6140), using the tool holder with the following parameters: rake angle γo = 6°, clearance angle αo = 6°, inclination angle λs = −7.2°. Machining conditions are shown in Table 4. The cutting forces were measured by using piezoelectric quartz dynamometer (Kistler9293A, Switzerland) in the experiments. Worn surface of the tool and chip morphology were observed by scanning electron microscope (SEM).

## 4 Results and discussion

### 4.1 Cutting forces

Figure 4 presents the cutting forces of NCT and VCT tools at different cutting speeds during machining simulation of Ti6Al4V. In general, VCT tools could reduce cutting forces compared with those of NCT tool. From Fig. 4a, a maximum main cutting force of 190.41 N was observed for NCT tool at the cutting speed of 60 m/min. Compared with that of NCT tool, the main cutting forces of VCT1, VCT2, and VCT3...

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**Table 4 Cutting parameters used in cutting experiments**

| Cutting speed (m/min) | 60, 90, 120 |
|-----------------------|-------------|
| Depth of cut (mm)     | 0.5         |
| Feed rate (mm/rev)    | 0.1         |
| Cutting time (min)    | 5           |
| Lubrication           | Dry and emulsified cutting fluid |

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*Fig. 3* Four types of cutting tools (a–e) and morphology of volcano-like texture (f)
tools were reduced by 7.6%, 9.1%, and 4.4%, respectively. The results showed that the introduction of volcano-like textures lowered the main cutting force. Among all cutting tools, it was observed that the main cutting force of VCT2 tool was the minimum (173 N), which illustrated that the texture area density had optimal value (20%). As the cutting speed increased from 60 to 120 m/min, the main cutting force of VCT2 tool was reduced by 11.06%. The reduction in the main cutting force as the increasing speed is due to greater chip plastic deformation and reduced friction on the tool-chip/workpiece contact interface, and the chip is softened by the continuous cutting heat generated.

In Fig. 4b, the maximum radial force of 87.1 N was noticed with NCT tool at the cutting speed of 60 m/min. Under the same machining conditions, the minimum radial force of 73.2 N was found with VCT2 tool, which was reduced by 16.0% compared with that of NCT tool. The reduction in radial force can be attributed to the shorter tool-chip contact length/area and larger heat dissipation area for textured coated tool. With the cutting speed increasing from 60 to 120 m/min, the radial force of VCT2 was reduced by 16.3% compared with that of NCT tool.

Figure 5 depicts the comparison of cutting forces at 60 m/min, 90 m/min, and 120 m/min under simulative and experimental conditions. It was noted that the simulation results were in agreement with experimental results with deviation of only 1–10% due to precise definition of
material model and finite element mode for machining. VCT2 tool exhibited better results compared with other tools observed from Fig. 5. Meanwhile, there was a tendency with decreased initially and then increased both the main cutting force and the radial force. This was similar to the conclusion obtained from the spherical texture mentioned in literature [25]. Therefore, it was believed that the density of volcano-like textures had a great influence on the performance of the tool.

4.2 Friction coefficient

The average coefficient of friction on the tool-chip contact surface under experimental conditions can be computed based on the following formula [26]:

\[
\mu = \tan(\beta) = \tan(\gamma_0 + \arctan(F_y/F_z))
\]

where \( \gamma_0 \) is the rake angle, \( \beta \) is the friction angle, \( F_y \) is the radial thrust force, and \( F_z \) is the main cutting force.

Figure 6 shows the average friction coefficient of four tools at 60 m/min, 90 m/min, and 120 m/min. It can be seen that the friction coefficients of VCT tools were effectively reduced for any given speeds compared with NCT tool. The friction coefficient of four types of tools decreased as the increasing speed. The maximum reduction appeared on VCT2, whose fluctuations of friction coefficient decreased by 6.9–13.3%. Meanwhile, the VCT3 tool had a similar value with VCT1, which indicated that the higher value (30%) of area density negatively affected the friction behavior on the mating surface during the cutting process.

4.3 Cutting temperature

High cutting temperature is one of the main reasons for tool wear that directly affects cutting quality and tool life. The elastoplastic deformation of the primary and secondary deformation zones and the friction on the
tool-chip/workpiece interface are the main sources of cutting heat, which is predominately dissipated by the chip [27].

Figure 7 shows the temperature distribution on the chip produced by four types of cutting tools at 120 m/min. The initial temperature for the workpiece and tool was set as 25 °C. When the cutting process reached to a steady state, NCT tool had the highest cutting temperature (1030 °C) that was mainly distributed in chip root contacting the tool. For VCT1 and VCT2 tools, the highest cutting temperatures were 985 °C and 924 °C, respectively, which were lower than that of NCT tool at the same cutting speed. This can be explained as the volcano-like textures promoted the bending of the chip and reduced the contact area between the tool and the chip. Furthermore, the textured tool created a vacuum in the area where the chip was in close contact with the tool surface, which decreased the heat concentration on the tool surface. Thus, the volcano-like textures increased the convective heat transfer area between the tool surface and the air, which speeded up the heat dissipation. As the texture density reached to 30%, the cutting temperature was reduced by 6.0% compared with that of NCT tool. However, the cutting temperature was increased by 4.8% compared with that of VCT2 tool. Thus, appropriate texture density (10–20%) can reduce cutting heat generation in machining of workpiece material.

4.4 Chip morphology

Figure 8 depicts the chip generated by the four cutting tools under the simulative conditions at 120 m/min. It can be clearly seen that at step 1290, the chip back of the NCT tool was smoother than that of VCT tools. Micro-grooves pointed by the green arrow were found on the chip back of VCT tools because of the print effect of volcano-like textures. The above phenomena illustrated that the textures generated an inward force and promoted the chip bending in the tool-chip contact process. Therefore, the spiral chip with smaller radius was obtained for VCT tools.

Figure 9 shows the chip of four kinds of tools at the speed of 120 m/min under the dry and wet cutting conditions. Friction on the tool-chip interface is an important factor affecting the chip formation, such as its size and surface topography. Less friction at the contact zone facilitates the smaller curled radius of the chip [10]. From Fig. 9, the curling radius of the chip produced by the NCT tool was the largest in dry cutting, which was difficult to break and thus increased the frequency
of chip entanglement with workpiece and tool. Under wet cutting conditions, VCT tools obtained the chip with smaller radius compared with that of NCT tool due to the formation of a lubricant film on the tool-chip interface. It can be explained that the lubricant film can reduce the friction and shear force between the two.

**Fig. 9** Chip formation of NCT (a, b), VCT1 (c, d), VCT2 (e, f), and VCT3 (g, h) tools during machining experiments at the speed of 120 m/min under dry and wet conditions.

|     | Dry cutting | Wet cutting |
|-----|-------------|-------------|
| NCT | ![NCT a](image) ![NCT b](image) | ![NCT a](image) ![NCT b](image) |
| VCT1| ![VCT1 c](image) ![VCT1 d](image) | ![VCT1 c](image) ![VCT1 d](image) |
| VCT2| ![VCT2 e](image) ![VCT2 f](image) | ![VCT2 e](image) ![VCT2 f](image) |
| VCT3| ![VCT3 g](image) ![VCT3 h](image) | ![VCT3 g](image) ![VCT3 h](image) |

**Fig. 10** SEM images of chip free surface and microstructure obtained with NCT tool at the speed of 120 m/min in dry cutting (a–c) and wet cutting (d–f).
contact surfaces, promoting the bending of the chips and the chip-breaking efficiency.

Figures 10, 11, 12 and 13 show the SEM images of the chip free surface at the speed of 120 m/min. The curling radius of chip produced by different tools was measured with Image J software shown in Table 5. It was noted that the straight chip with larger radius was observed for NCT tool under dry cutting conditions. After supplying cutting fluid, the chip generated was spiral crimp with lower radius obviously. Compared with that of NCT tool, the chip-curling radius for VCT1, VCT2, and VCT3 tools was reduced by 36.4%, 49.7%, and 25.6%, respectively. Among these tools, VCT2 tool produced the smallest chip radius under the two cutting conditions, which illustrated that the introduction of the volcano-like textures and the changes of the cutting environment had a great effect on a contact state between the tool and the chip.

Figures 10, 11, 12 and 13 show the SEM images of chip free surface and microstructure obtained with different types of tools at the speed of 120 m/min in dry cutting and wet cutting. Serrated chips were formed at the primary and secondary surfaces in the process of machining Ti6Al4V because of the unstable plastic deformation with adiabatic shear. Due to the instability of the thermo-plastic flow, micro-defects appear in the shear surface, resulting in layer by layer slipping [28]. As Figs. 10–13 describe, the smoother free surface and less lamellar structures of NCT tool were observed compared with that of VCT tools. More friction was produced on the tool-chip interface and then caused high temperature, inhibiting the generation of lamellar structures of the NCT tool. In addition, the segmental chip space formed by VCT tools under wet cutting environment (considering the chip bending radius) was larger than that of dry cutting, namely the smaller segmentation frequency for the
chips [29]. This phenomenon was observed obviously as the increasing texture area density. Therefore, compared with that of NCT tool, VCT tools had a smaller chip segmentation frequency. Since chip segmental frequency was associated with chip stability, VCT tools reduced vibrating in the tool system.

Figure 14 shows the SEM images of the chip back surface of NCT and VCT2 tools at the speed of 120 m/min. From the high magnification of Fig. 14, it can be found that the back surface of the NCT tool was relatively smooth, while there were uniform arc-shaped grooves on the chip generated by VCT2 tool. These traces indicated that the convex texture can support the chip, which promoted the chip curling and the material removal. These phenomena were consistent with the chip simulation results in Fig. 8.

4.5 Surface wear

Figure 15 shows the wear depth of the rake face of the four types of cutting tools under the simulative conditions at 120 m/min. Tool wear was concentrated at the rake face extending to the periphery in a gradient, and the area with highest wear degree was near the cutting edge. From Fig. 15b–d, the maximum wear of VCT1, VCT2, and VCT3 tools were 0.421 μm, 0.413 μm, and 0.430 μm, respectively. Therefore, the maximum wear of VCT2 tool was the smallest compared with that of NCT tool, which was reduced by 8.0%. In general, the introduction of texture reduced the surface wear of the tool under the simulative conditions, and VCT2 tool exhibited better wear resistance than other coated tools.

In order to further understand the wear mechanisms under simulative conditions, the worn surfaces of the tools after cutting experiment were studied. The large tool-chip contact length/area, high cutting temperature near the tool tip, and lack of proper lubrication will cause tool surface wear, which decreases the service life of the tool [30].

Figure 16 shows the marks of adhesion area on the rake face of NCT and VCT tools. Adhesion area of NCT tool was obviously larger than VCT tools. According to Fig. 17, compared with that of the NCT tool, the adhesion area of VCT1, VCT2, and VCT3 tools under dry cutting conditions was decreased by 8.6%, 17.4%, and 9.7%, respectively. Therefore, it can be seen that VCT2 tool exhibited less surface adhesion and wear. As the cutting speed increased from 60 to 120 m/min, adhesion area of the four types of cutting tools enlarged with the area of NCT tool reaching to 81.8%. With the increasing cutting temperature, more softened chips adhered on the surface of the tool. The cutting regions experienced a “formation–stacking–plucking” process. Due to this repetitive process, the workpiece material on the tool surface was teared by the sliding chips, causing adhesion wear on the tool surface. In Fig. 18, the adhesion and wear on the rake face for the NCT tool was more obvious, while less wear on the surface of VCT2 tool was observed. This is
because the existence of the volcano-like textures reduced the length of the tool-chip contact. And it can be seen that there was debris inside the concave part of the texture, which reduced the scratches on the tool surface.

Under wet cutting conditions, similar wear pattern appeared on the tool surface in Fig. 19. At 60 m/min, the adhesion area of the four types of cutting tools was reduced by 7.3%, 17.1%, 15.2%, and 7.7%, respectively, compared with that of dry cutting. The cutting fluid acted as not only coolant but also lubricant, which can help to carry away the debris formed in cutting process and then alleviate the tribological state of the tool-chip contact surface and reducing the generation of cutting heat. In Fig. 19c,d, the volcano-like textures increased the air gap between the tool-chip interface, which can transmit the cutting fluid to the sticking and slip zones. Therefore, only a small amount of adhesion and wear on the tool surface was found.

4.6 Mechanisms for the effect of volcano-like textured coated tool

Results of this study show that the volcano-like textures result in a dramatic reduction in cutting forces, cutting temperature, and tool wear, especially for the VCT2 tool. The mechanisms behind the improvement of wet cutting performance in VCT tools are discussed next.

The schematic diagram of the contact interface between the tool and the chip is shown in Fig. 20. It can be noted that the volcano-like texture is a composite morphology containing concave and convex regions. Under wet cutting conditions, the contact region between the volcano-like textures and the chip was peak-point contact, while NCT tool was in a compact surface contact. Therefore, VCT tools can decrease the contact area between the tool-chip interface. As a result, the cutting forces and cutting temperature were reduced largely. From Fig. 3f, it can be found that the bulge of the volcano-like texture was relatively mild. Hence the texture can play a role in holding up the chips when the chip slid across the rake surface. And it can also provide a fulcrum and promote chip curling. In “Section 4.3,” the volcano-like textures increase the heat transferring area and accelerate the heat convection with air and cutting fluid, which help in the reduction of the adhesion and wear on the rake face [14]. With the existing region of concave morphology, the textures can retain a mass of wear debris generated during the cutting process, which reduces the friction as well as damage on the tool surface. Besides the textures can efficiently promote cutting fluid penetrating into the mating face.
**Fig. 15** Wear depth of four types of cutting tools at the speed of 120 m/min under simulative conditions.

**Fig. 16** The marks of adhesion area on the rake face of NCT tool (a) and VCT tools (b).
Fig. 17 Adhesion area of four tools in dry cutting (a) and wet cutting (b)

Fig. 18 SEM images of tool wear after cutting at the speed of 60 m/min and 120 m/min under dry cutting conditions
The concave regions of the volcano-like textures act as a micro-pool for cutting fluid. Figure 21 shows the micrographs of the wear track and the corresponding EDS analyses at the rake surface of NCT tool after wet cutting at the speed of 60 m/min. From Fig. 21, it can be seen that there is very little Na element (0.07%) at the worn face. NCT tool almost had no lubrication fluid permeating into the worn surface. However, it is evident that a large amount of Na element can be seen on the worn surface for VCT tools from Figs. 22, 23 and 24. For instance, VCT2 tool had the maximum value of Na element content, accounting for 1.97%. Thus, the volcano-like textures can help cutting fluid transmit into the tool-chip contact zone compared with other coated tools. Meanwhile, the Na element also was found on the concave region of textures, indicating that the volcano-like textures can retain the cutting fluid that provide a continuous lubrication. Therefore, VCT2 obtained a better machining performance among all kinds of tools.
Fig. 21  Na element on the worn surface of NCT tool after wet cutting at the speed of 60 m/min

Fig. 22  Na element on the worn surface of VCT1 tool after wet cutting at the speed of 60 m/min
Fig. 23 Na element on the worn surface of VCT2 tool after wet cutting at the speed of 60 m/min

Fig. 24 Na element on the worn surface of VCT3 tool after wet cutting at the speed of 60 m/min
5 Conclusions

In this study, in order to study the effect of different densities of volcano-like textures on the cutting performance of CrAlN coated tools, FEM cutting simulation was firstly performed in DEFORM-3D software to predict the cutting forces, cutting temperature, friction coefficient, chip morphology, and tool wear. Then dry and wet cutting experiments were carried out to validate the FEM simulations. Main conclusions are obtained as follows:

1. The experimental results were consistent with the simulated results, which validated the credibility of the FEM simulation. Volcano-like textures on the tool surface significantly reduced the cutting forces in wet cutting. The main cutting force was reduced up to 11.6% compared with that of NCT tool. And the textures improved the friction state on the tool-chip contact interface according to the less friction coefficient.

2. The cutting temperatures of VCT1, VCT2, and VCT3 tools were reduced by 4.4%, 10.3%, and 6.0%, respectively, compared with that of non-textured tool. Less heat reduced tool wear during machining especially under lubricating conditions.

3. Through simulative and experimental investigation, it is shown that texture area density had a great influence on the tool surface properties. And VCT2 tool exhibited better cutting performance.

4. The physical mechanisms responsible for the improvement of cutting performance and tool wear are found. The volcano-like textures can reduce the tool-chip contact length/area and promote the chip curling. In wet cutting, the textures can be helpful in carrying and entrapping the cutting fluid and debris, thus reducing the damage of tool surface.

Author contribution Conceptualization: YZ, YF; methodology: YF; formal analysis and investigation: YZ; writing - original draft preparation: YZ; writing - review and editing: YF, JY; funding acquisition: YF; resources: YF; supervision: YF.

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Availability of data and material The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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