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Experimental investigation of microtextured cutting tool performance in titanium alloy via turning

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ABSTRACT

This study aimed to prevent the harmful consequences of the turning process. The use of micro-textured cutting inserts with a femtosecond laser an innovative efficient method to decrease chip adhesion to cutting of edge tools during titanium alloy (Ti6Al4V) turning was studied. Additionally, the effects of different micro-pattern geometries and sizes on the machining capacity of coated WC/Co cutting inserts in turning experiments with titanium–aluminium–nitride (TiAlN) were investigated based on various lubrication processes. The surface states of the micro-patterned TiAlN-coated inserts were analysed using scanning electron microscopy and optical microscopy. Subsequently, machining and measured tests on the titanium alloy were performed using the developed cutting tools. Tungsten carbide tools with textured cutting surfaces and different microstructures were fabricated, and their behaviours were compared with those of conventional coated tools. Thrust, cutting, and feed cutting force values were measured during machining using a three-component dynamometer. Based on the present investigation, the cutting tool with a cross texture exhibited greater reduction of machining forces, friction coefficients, and tool wear.

1. Introduction

Obtaining a high final quality of manufactured components is the main challenge in the mechanical industry when using chip-removal processes such as milling and turning. The latter is generally used in many circumstances, such as in the cylindrical turning of mechanical components according to the requirements for dimensional and geometrical tolerances and surface quality. In addition, the final quality of a workpiece is significantly affected by the process parameters, which can often cause tool deflections. Moreover, wear is undesirable deterioration of cutting inserts during workpiece machining and chip removal. It automatically involves the replacement of cutting inserts while considering the economic aspects of turning operations. In fact, a comprehensive understanding of the tribological behaviour of the cutting insert/workpiece pair and the study of implementation of their inserts is crucial. This is because the state of the workpiece surface and the dimensions to be observed are significantly affected by the cutting edge wear, which degradeds the surface final quality to be machined and the accuracy of the imposed shape. Improving the performance, efficiency, and lifespan of cutting tools has remained challenging (see Fig. 1). This is because the cutting force values, heat generation, and friction coefficient value must be simultaneously decreased.

Fig. 2(c) schematically shows depicts the different types of edges used in most cutting inserts, specifically a sharp edge, chamfer edge, double chamfer edge, and radius edge, ands well as the three missing regions of the blunt (zone 1), double chamfer (zone 2), and chamfered cutting inserts relative to the cutting tool (zone 3).

Recently, surface micro-texturing has been proposed to improve the tribological characteristics of solid surfaces in dry or lubricated contact. Micro-reservoirs created on a solid surface indicated a decrease in surface degradation during contact compared with smooth surfaces, and they provided a lower coefficient. Moreover, they reduced the adhesion to the cutting edge tool and workpiece interface and conferred effective lubrication to the contact; that is, they modulated the tribological properties. This clear enhancement was primarily on account of several mechanical and tribological phenomena, such as the local increase in the supply of lubricants by the fabrication of micro-dimples of fluid, the increase in transfer capacity by the hydrodynamic effect, and the trapping of wear debris.

For example, Borghi et al. [3] indicated that texturing of nitrided steel surfaces at the micrometric scale provided a much lower friction coefficient than that measured on the same smooth surface. Wu et al. [4]

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used the micro-textured surface of a cutting tool to study its effect on the tribological behaviour, namely the friction coefficient and wear. The results clearly indicated that the microstructures decreased the friction coefficient value by up to 35% compared with the smooth surface used as a reference. Sugihara and Enomoto [5] tested the tribological behaviour associated with the performance of micro-textured cutting inserts during milling. Laser-textured cemented carbide cutting faces yielded an efficient improvement and provided good lubricating power that significantly decreased the adhesion of the cutting insert/workpiece when milling aluminium alloys. Mishra et al. [30] evaluated the effect of nanosecond pulsed laser textured cutting inserts in both environments during the turning of Ti6Al4V alloy. They found that both MQL lubricants resulted in reduced cutting and thrust forces, as well as an apparent friction coefficient. The results for the nano-MQL were further enhanced by the formation of a tribofilm of deposited/agglomerated nanoparticles at the texture patterns. Shum et al. [6] produced micro-patterns perpendicular to the surface of the workpiece for machining. Their experimental results indicated that diamond-like carbon coatings with a reservoir rate of 10% improved the cutting behaviour of machining tools in terms of friction and wear performance compared with the original coatings without texturing.

Furthermore, Kim et al. [7] investigated the effect of a structured cutting tool on the tribological properties of cutting the insert/part contact for hard machining. The micro-patterned cutting insert decreased the force and improved the flank wear at a lower surface speed and feed rate compared with those of untextured cutting tools. Sawant et al. [8] investigated the influence of textures on the rake face of HSS cutting inserts in the turning of Ti-6Al-4 V titanium alloy under dry conditions. It was found that better performance in terms of cutting temperature, surface roughness, and cutting/thrust forces for the evaluated cutting conditions were obtained when using dimple-textured HSS tools. In fact, because of their shapes, the spot textures led to an early separation of the chip from the rake face, which improved the convective heat transfer of the turning process, which that, in turn, increased the tool life. Kawasegi et al. [9] performed machining tests on titanium alloys based on patterned cutting inserts with groove dimensions varying from a few micrometers to several nanometers oriented in perpendicular and parallel directions. Reduced cutting force and low friction coefficient were measured for cutting inserts that were perpendicular to the pattern relative to the flow of chips.

Moreover, S. N. and G. L. S. [155] investigated the drilling process of Ti6Al4V alloy using uncoated cemented carbide drills containing circular micro-dimples obtained by Nd-YAG laser micromachining. The drilling revealed a significant reduction in titanium deposited on the textured tool compared to the non-textured tool under different lubrication conditions. The authors concluded that the surface texture minimised the burr formation at the exit of holes on account of the enhanced heat dissipation at the cutting interface. Zhou et al. [10] investigated the effectiveness of parallel texturing on cutting tools during the down-end milling of Ti6Al4V alloy. Compared to the non-textured tool with conventional cutting fluid, the tool wear rate was decreased owing to the better wettability and spreadability of the nanofluids in the texturized surface. This promoted a more stable lubrication film at the tool–chip interface. Patel et al. [11] evaluated the effects of micro-textured tools created using micro-EDM in the dry machining of Ti6Al4V titanium alloy. They found that the cutting forces notably increased as the distance between the pattern and depth increased, resulting in a substantial increase in the cutting temperatures and wear rate.

In addition, Su et al. [12] used diamond tools with parallel micro-grooves to study the performance of textures on diamond tools in the dry turning of Ti6Al4V titanium alloy. Despite using cutting inserts without lubricants, the authors found that the tool–chip interface frictional behaviour was significantly improved when using the micro-textured cutting inserts compared to that of the smooth cutting inserts. Arulkirubakaran et al. [13] investigated the performance of textured cutting inserts in the machining of Ti–6Al–4V alloy using a mixture of MoS2 and SAE 40 oil (80,20) as a semi-solid lubricant. The micro-grooves textured in parallel, perpendicular, and cross patterns to that of chip flow orientations were obtained using wire EDM. They concluded that the best results were in the textures with the perpendicular pattern, which better reduced the friction forces and improved the lubrication in the tool–chip contact interface.

Moreover, Arulkirubakaran et al. [14] investigated the effect of EDM surface textures on an uncoated cemented carbide insert. They analysed the machinability of the Ti-6Al-4 V alloy during turning under semi-solid lubrication using cutting inserts with grooves that were parallel, perpendicular, and oblique to the chip flow direction. The authors found that the surface textures on the tool significantly reduced the machining forces under lubricated conditions.

The present study evaluated the effect of areal textured tools on the turning of Ti-6Al-4V alloy under different lubricant conditions. A method is herein proposed to improve the machinability of cutting tools and mitigate the deleterious effects that occur during the cylindrical turning of titanium alloy. An investigation was performed using different texturing and densities fabricated on a smooth surface of the inserts for cutting finishing tools. The principal cutting force, thrust force, and feed force were measured for all the machining conditions. In addition, the tribological performance of these micropatterned cutting inserts was studied. Finally, the tool wear after machining was examined using an optical microscope. According to the experimental results, the cutting tools with cross textures exhibited better results. The cross pattern could not only change the texture capacity to store and deliver the lubricant, but they could act as a chip flow. Therefore, the rake face with the cross microgroove tendsed to decrease the system wettability by improving its lubrication properties. These tools also showed better tribological behaviour.

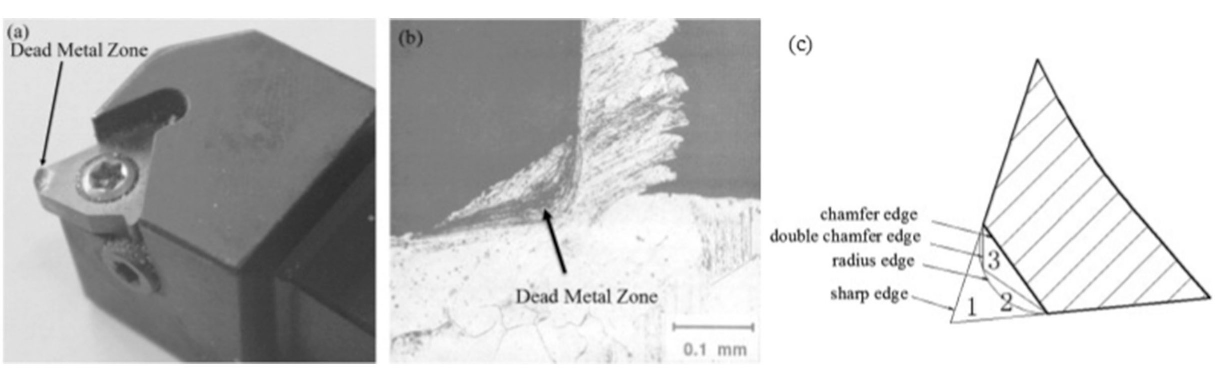

Fig. 1. Photographs of a tool with cutting insert: (a) a blunt spout, (b) dead metal zone, and (c) peak shapes of cutting inserts [1,2].

2. Material and experimental procedure

2.1. Material

The cutting inserts selected for the experiments were made of commercial grades of cemented carbide alloys using ceramic cutting inserts with a titanium–aluminium–nitride (TiAlN) coating. Cemented carbide finishing inserts with a TiAlN coating (GC6050) and cutting inserts with a ratio of 96% vol. WC and 4% vol. Co provided by the Sandvik Company was used. The cutting surface used was smooth, without a chip breaker. To study the effect of micro-patterns on the cutting behaviour during machining and the tribological properties of these tools, their rake surfaces were micro-patterned with various dimples or micro-textures either in the cross, parallel, or perpendicular direction to the chip movement.

A conventional titanium alloy (Ti-6Al-4V) from cylindrical bars measuring 200 mm in length and 50 mm in external diameter was used. The mechanical properties of the workpiece were as follows: density, 4.3 g.cm^{-3}, Poisson's ratio, 0.342, and HRC 50–60 hardness.

2.2. Femtosecond laser treatment

The micro-dimple and groove patterns were fabricated on the smooth surface of the rake close to the cutting-edge area (see Fig. 2). The femtosecond laser (with a diameter of 5 mm) was focused on the smooth areas of the cutting inserts by a focal distance of 20 cm to generate a spot diameter of approximately 5 μm on the focal plane. Furthermore, laser tests were performed by moving the cutting inserts beneath the stationary beam laser by pulsing the laser beam at 1 kHz at a constant scanning speed. However, a femtosecond laser with a wavelength of 800 nm and a pulse duration and repetition rate of 100 kHz and 120 fs, respectively, were retained to generate these different micro-patterns. The laser energy and laser fluence used in our experiments were respectively 0.6 μJ and 0.083 J/cm^2. The scanning speed and overlap between the pulses were respectively 3.3 m/s and 90%.

The laser was used to generate dimples or grooves with an average depth of approximately 4 μm on the surfaces of the coated samples (coating thickness was approximately 5.5 μm). Dimples with an average diameter of 10 μm and a groove width of 10 μm were created by varying the pitch (see Table 1). All sample surfaces were studied and carefully observed using optical microscopy (i.e. before and after patterning).

The micro-texturing of the cutting tools was performed close to the smooth area of the cutting insert in different orientations and using three different densities of micro-patterns, that is, 10%–30%. Five cutting inserts with four types of microscale patterns were fabricated and tested: (a) original inserts without microstructures, (b) and (c) textures perpendicular or parallel to the cutting edge, (d) crossed textures, and (e) micro-reservoirs. A schematic representation of the details of each

Table 1
Geometric characteristics of microstructures.

	Tool name			
Dimensions	TTT	PTT	TPT	CTT
L_1 [mm]	6	6	2	2
L_2 [mm]	2	2	6	6
A [μm]	30-40-50	–	–	–
B [μm]	30-40-50	–	–	–
C [μm]		90-40-25	90-40-25	90-40-25
ØD [μm]	10 ± 2	–	–	–
E [μm]	–	10 ± 2	10 ± 2	10 ± 2
H [μm]	3.5 ± 0.5			
α [%]	10-20-30			

pattern is presented in Fig. 3. The different micro-patterns illustrated in Fig. 3(b) to (d) correspond to laser manufacturing in the dynamic mode, whereas that in (e) shows the static mode. After laser texturing, the tool area was cleaned ultrasonically to remove residues. The dimensional and geometrical characteristics of the textures are listed in Table 1.

Three fractional densities of microstructures (micro-dimples or microgrooves) were textured on a surface measuring approximately 12 mm^2 (see Fig. 4(a)). Furthermore, α (%) was used in this study with reservoir rates of 10%–30%, as illustrated in Fig. 4(b).

Fig. 5 shows a schematic description of the parameters considered to calculate the density rate of the micro-textures for reservoirs or grooves. Table 1 summarises the geometric dimensions that have been developed. The density of each textured surface was calculated using the following equation:

$$\alpha\,(\%) = N.S_{concave}/(S_{concave} + S_{convex}) \quad (1)$$

where S_{convex} and S_{convex} are the convex and concave areas of each textured rake face, respectively.

2.3. Surface characterization

The textured surfaces of the cutting inserts after laser processing and before the turning tests were analysed using optical microscopy (Keyence VHX-600E) and scanning electron microscopy (SEM). The micro-textured functional surfaces did not undergo any polishing before or after texturing. Surface images of the regions measuring 50 × 50 μm^2 were acquired.

2.4. Surface-wetting characterization

Static wetting angle measurements were performed on droplets of deionised water or lubrication fluid deposited on the surface of samples measuring 12 × 12 × 4.76 mm^3 using a micrometric syringe. The volume used was 4 ± 0.1 μL. The relative humidity and temperature were

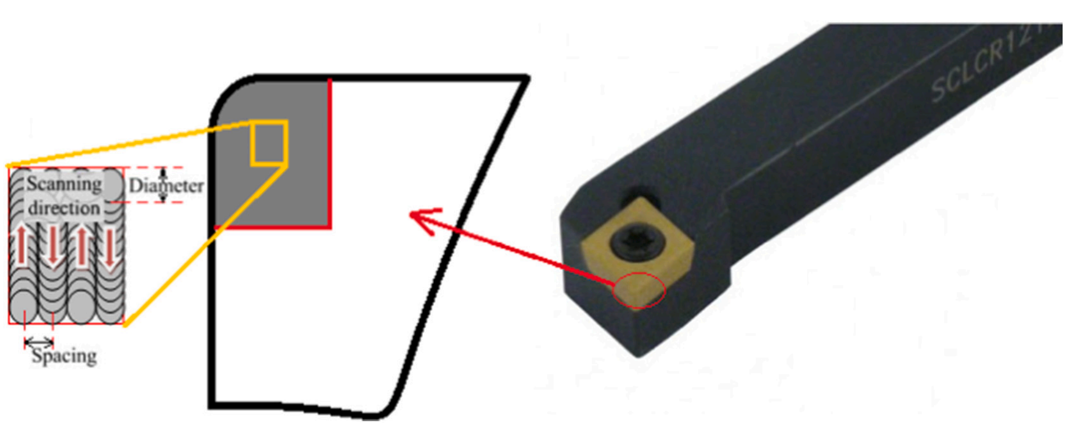

Fig. 2. Descriptive schema of texturing of cutting inserts using dynamic mode by femtosecond laser.

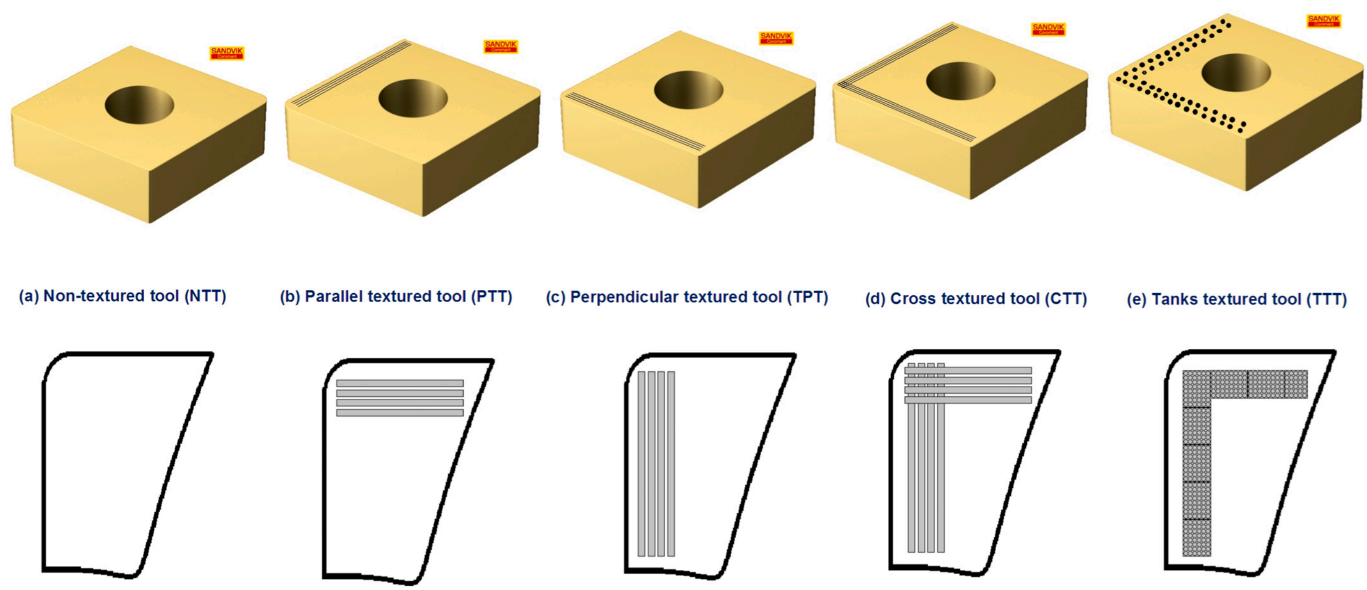

Fig. 3. Descriptive images of micro-patterns using various micro-patterns textured by femtosecond laser on cutting face of machining tools: (a) smooth original cutting insert (NTT), (b) Parallel textured tool (PTT), (c) Perpendicular textured tool (TPT), (d) Cross-textured tool (CTT), and (e) Dimple textured tool (TTT).

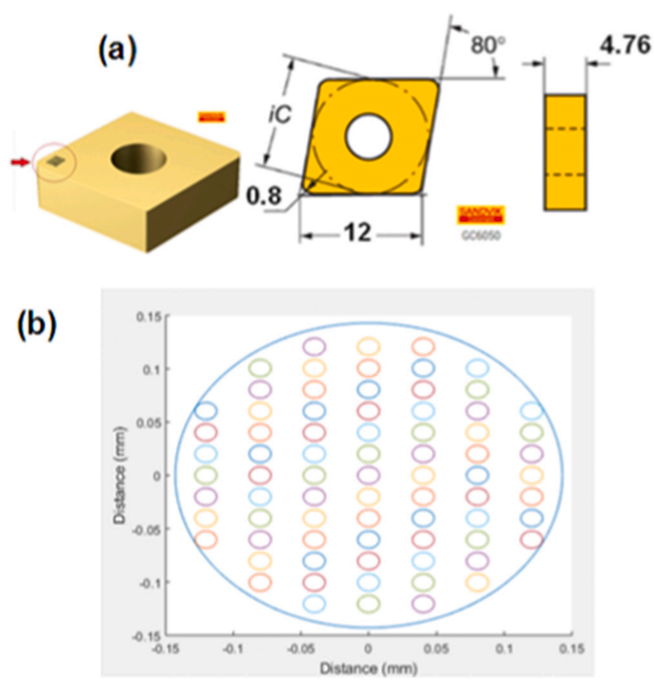

Fig. 4. (a) Illustration of a cutting insert with its dimensions, and (b) different micro-textured fractions on rake face.

maintained at 25 ± 2% and 21 ± 1 °C, respectively. The contact angle of the droplet obtained using an imaging camera was measured using axisymmetric drop shape analysis (see Fig. 6). At least six comparative tests were performed for each case.

2.5. Machining tests

Longitudinal turning experiments were performed on a CTX 320 linear Gildemeister CNC lathe. The machining operations were realised using cutting inserts with the following parameters: inclination angle $\lambda_s = 0°$, draft angle $\alpha_o = 7°$, rake angle $\gamma_0 = -5°$, and edge angle lateral cutting $K_r = 45°$. All the turning experiments were performed using the following parameters: feed speed f = 0.1 mm/revolution, cutting depth $a_p = 0.3$ mm, and cutting speed 40–200 m/min. A dynamometer (Kistler Co., Ltd., 9257B) was used to measure the cutting force values in the turning machining experiments.

2.6. Tribology tests

The friction and wear properties of the cutting tool surfaces were tested using starved or full lubrication conditions. Before each test, the balls and cutting inserts were cleaned in absolute ethanol for 5 min and then dried in air to remove residual dust and other solid contaminants. Tribological tests were performed at room temperature (20 ± 1 °C) in ambient air with a relative humidity of 30 ± 5% at unidirectional using a tribometer achieving reciprocating linear motion with a ± 1 mm displacement stroke at 1 Hz. Bearing 100Cr6 steel balls 6 mm in diameter were slid against cutting tool surfaces using an Anton-Paar tribometer with a sliding distance of 40 m using commercial cutting oil.

Sliding tests were conducted under a normal load of 5 N. The sliding speed was 4 mm/s (N cycles = 10,000 backward and forward friction cycles). The tests were repeated six times with both a textured sample and an untextured control sample prepared in the same way. The viscosity of the cutting oil was determined to be 0.0316 Pa.s using a rotational rheometer a (Thermo Fisher) with coaxial cylinders at 20.2 °C and shear rates between 10 and 1000 reciprocal seconds.

3. Experimental results and discussion

3.1. Surface morphology

Optical images and SEM micrographs of the laser surface microtexture are shown in Figs. 7–10. Fig. 7(a) shows a three-dimensional (3D) image of the untextured area. The round-shaped micro-patterns were fabricated with homogeneous periodic structuring using optimal laser parameters, that is, laser energy density and pulsed number (see Fig. 7(b), (c), and (d)).

Figs. 8 and 11 show the surface topographies before and after laser ablation of the micro-patterned cutting inserts in the flat area of the rake, respectively. The colour variation in the illustration represents the modified topography in terms of the elevation face roughness of the cutting inserts after laser treatment.

Two-dimensional (2D) profilometry was conducted based on three

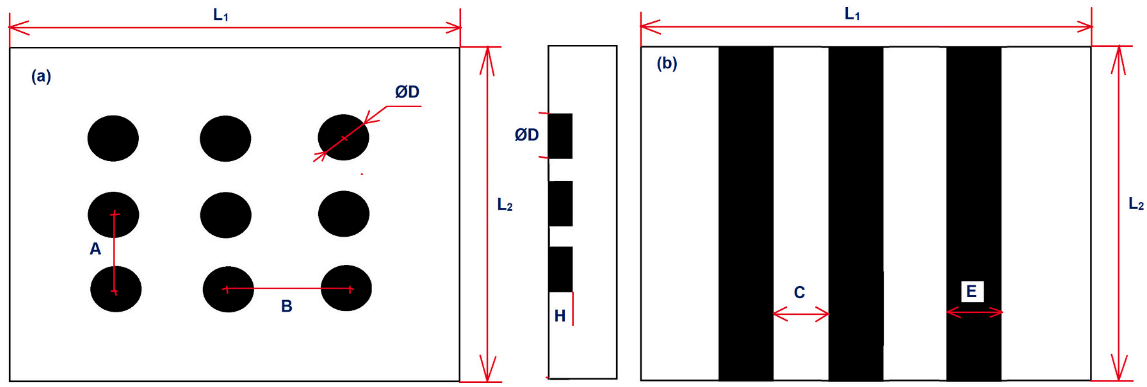

Fig. 5. Geometric parameters of (a) the micro-textures reservoirs (TTT) (a) and (b) grooves (PTT).

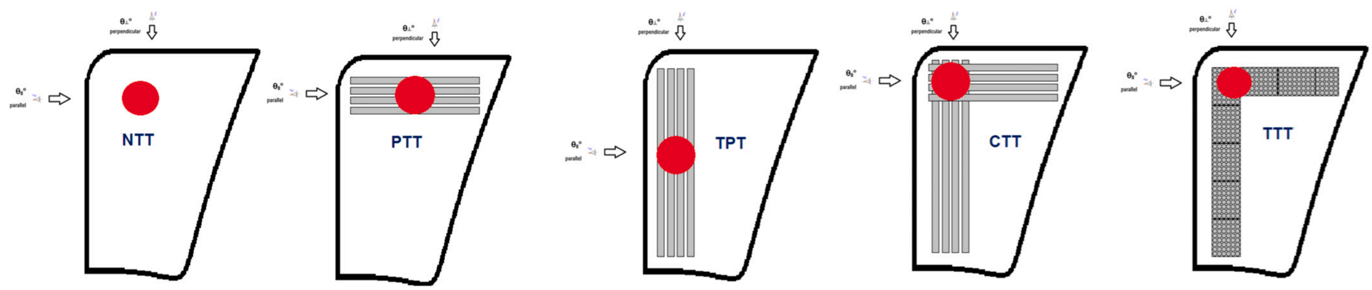

Fig. 6. Descriptive diagrams of contact angle measurement on micro-textured or smooth surfaces in two directions.

different density values (α), and the obtained shape profiles are shown in Fig. 9. They were measured using all the profiles perpendicular to the pattern and revealed that the homogeneous structure after laser ablation was obtained appropriately.

The tribological surfaces of the different specimens were analysed using SEM. Periodic and round-cell microprojections with clear definitions were obtained. As the laser fluence exceeded the ablation threshold of the material, the thermal effects were difficult to eliminate completely, which resulted in the formation of minor recoils in the molten material. Fig. 11 shows the SEM images of dimples and grooves textured on the coated cutting inserts with different laser energies. The microscopic patterns generated were either micro-dimples or linear grooves that were perpendicular to, parallel to, or intersecting the cutting edge with a depth of 4 μm and a width of 10 μm.

3.2. Modification of wetting properties

The analysis and measurement of the contact angles of the lubricating fluid droplet are critical to fully understanding the effect of micro-textures on the cutting face of the inserts by acting strongly on the contact area of the cutting insert/chip and wear mechanism. Generally, the contact angles in two perpendicular directions (perpendicular and parallel to the chip flow) have been mainly measured to characterise the degree of anisotropy of the micro-textured surfaces of the cutting inserts. In this context, the anisotropic behaviour of textured cutting surfaces with patterns of different shapes was studied. The contact values in the directions perpendicular ($\theta\perp$) and parallel ($\theta\|$) to the micro-textures were measured for three different surface densities. The value of the static contact angle on the entire laser-induced smooth surface of the cutting tool was $36.4^\circ \pm 1^\circ$, indicating the hydrophilic nature of the smooth surface (see Fig. 12). As a result, the smooth surface showed ordinary hydrophobicity because a large contact area resulted in a greater van der Waals force.

The photographs of the lubrication fluid contact angle measurements shown in Fig. 13 indicate that the surface coverage was good, as the contact angles of the lubricating oil between the smooth and textured surfaces differed completely. As a result, the femtosecond laser structured domain shows super-hydrophobicity with ultra-high lubrication fluid adhesion owing to its rough structure. These experimental data are consistent with the results reported by Hao et al. [15], who studied the yield of machining patterned cutting inserts during turning. The wettability results obtained using textured cutting tools showed the best cutting performance compared to the untextured and textured cutting tools.

The average contact angle and the associated error bars versus the smooth original cutting inserts of different sizes, shapes, and micro-textures for each surface were compared using water (see Figs. 13 and 14) and lubricating fluid (see Fig. 15). The smooth surface of the coated cutting inserts showed extremely low anisotropic wettability (see Fig. 13). It was also observed that the densities of the microstructures in the cutting inserts had an important effect on the lubrication fluid contact angle under the as-prepared surfaces. The droplet may have partly infiltrated microgrooves and enhanced the directional spreading of the droplet along the grooves for capillary action. The contact angle of the micro-textured surfaces decreased as the surface density of the patterns increased, as illustrated in Fig. 13. The contact angle values of the microscale surface (NTT) were greater than those of the other textured surfaces when the roughness factor decreased owing to the microscopic patterns produced by the femtosecond laser. The droplet more properly wetted the cross-structured surface (CTT). Recently, many studies have also demonstrated that the capillary effect in open microgrooves plays a dominant role in the directional guiding and flow of the lubrication fluid [16,17].

In addition, the $\theta\perp$ contact angle of the microgrooves was slightly larger than the $\theta\|$ contact angle; therefore, their $\Delta\theta$ was greater than those of the textured surfaces (TTT and CTT), as shown in Fig. 14. The micrometric structure orientation was the primary reason contributing to these favourable performances, which resulted in cavitation flow and low surface energy. The grooved patterned surfaces (PTT or TPT) showed clear anisotropic wettability. In addition, the coated surface TTT

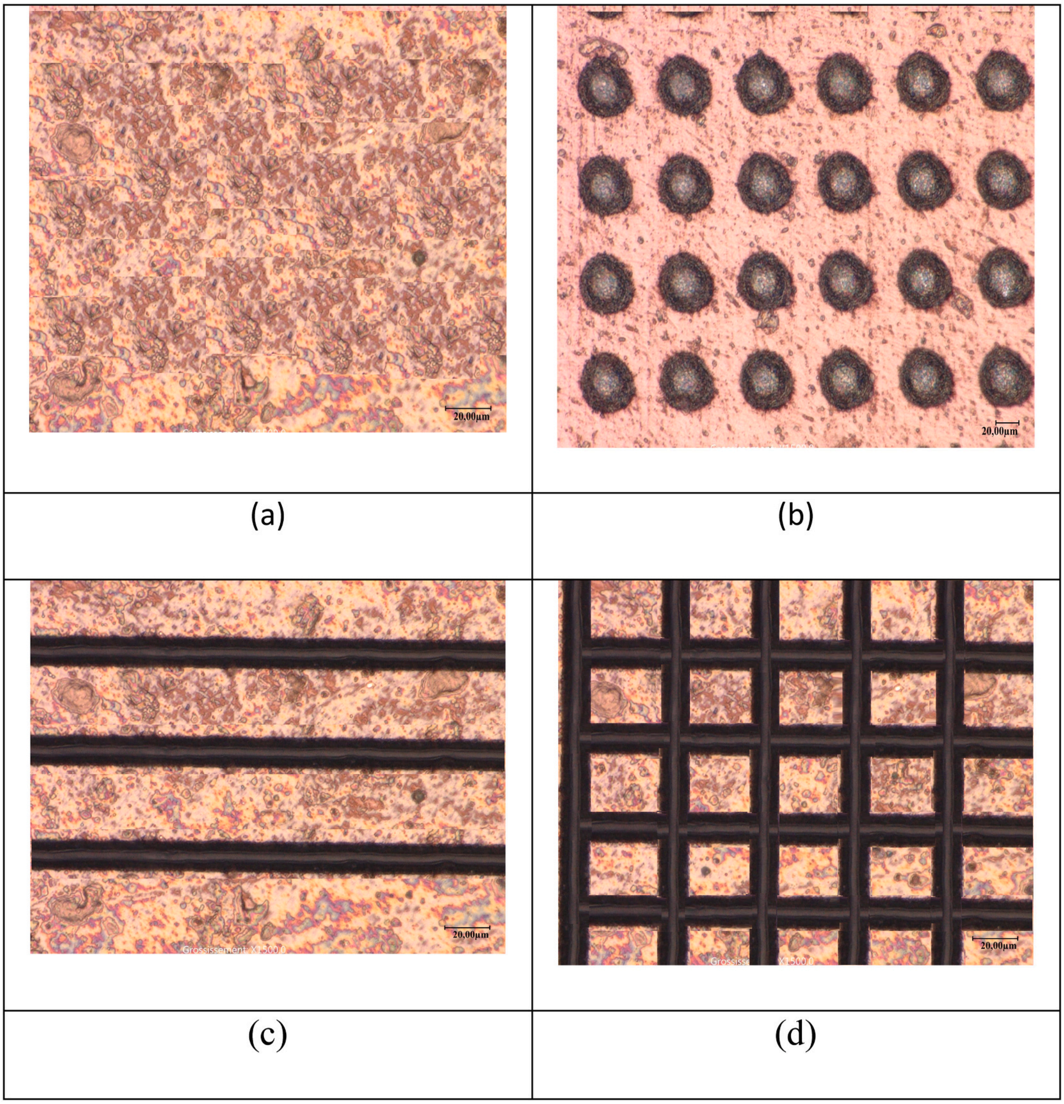

Fig. 7. Morphology of(a) initial untextured area (NTT), (b) dimpled shape (TTT), (c) parallel (PTT), and (d) cross microgroove textured area (CTT).

had a contact angle of 24.1 ± 1°, which was lower than the contact angle on the smooth surface NTT (36.4° ± 1°). After texturing, all contact angles were less than 29.6 ± 1°, and Δθ became significant, thereby proving the importance of the anisotropic wetting behaviour. However, the water droplets on the coating surface with groove patterns (PTT) showed more pronounced anisotropic behaviour, as presented in Fig. 14. The superficial morphology of the droplet in the PTT and TPT cutting tools induced preferential liquid imbibition along the micro-grooves and liquid pinning in the perpendicular direction. These experimental results agree well with the observations of Lee et al. [18] and Liang et al. [19].

The contact angles measured on the textured surfaces of the cutting inserts coated with water or lubricating fluid are shown in Fig. 15. The maximum and minimum values of the error bars were obtained for the six tested samples. The contact angles between the water and lubricating fluid were similar, with relative differences of less than 17%. All textured surfaces, except the smooth surface, were completely wetted with lubricating oil, indicating excellent wettability. In addition, it was clear that the texturing effect from the shape, direction, and density on the contact angle in the cutting insert was less pronounced for lubricating oil than for water. The contact angle measured with water was 28.4° ± 8°, whereas it was 15.7° ± 4° with the lubricating fluid. This indicates the feasibility of anisotropic fluidic shape control and ensures a good distribution of fluid on the cutting insert surface.

Oleophobic anisotropic surfaces (CTT) were successfully fabricated, in which the final contact angle was smaller than 10°. The micro-textured surfaces (CTT) with coatings indicated good wettability on the cutting surface; however, the effects of their tribological behaviour in the machining process are remained unclear. The contact angles along various directions were different for the anisotropic microstructures, and the droplet shape was strongly affected by the presence of oriented micro-features ([20]; Park et al. [21]).

3.3. Effect of fractional area of micro-patterns

Fig. 16 illustrates the tribological effects of the patterned area on the reduction in the coefficient of friction during contact between the treated cutting insert and workpiece. An industrial lubricant for machining with a shear viscosity of 1.1 mPa•s was tested. The microstructures significantly reduced friction. Three different densities of microstructures were tested to determine the minimum density required to achieve a low friction coefficient. Better performance was obtained when the fractional region of the microstructures was greater than 8%. Furthermore, when the density was equivalent to 20% of the micro-patterns, the friction coefficient decreased significantly by 18%, that is, a small tribological effect was produced (see Fig. 16). The cross micro-textures (CTT) significantly reduced the friction coefficient by

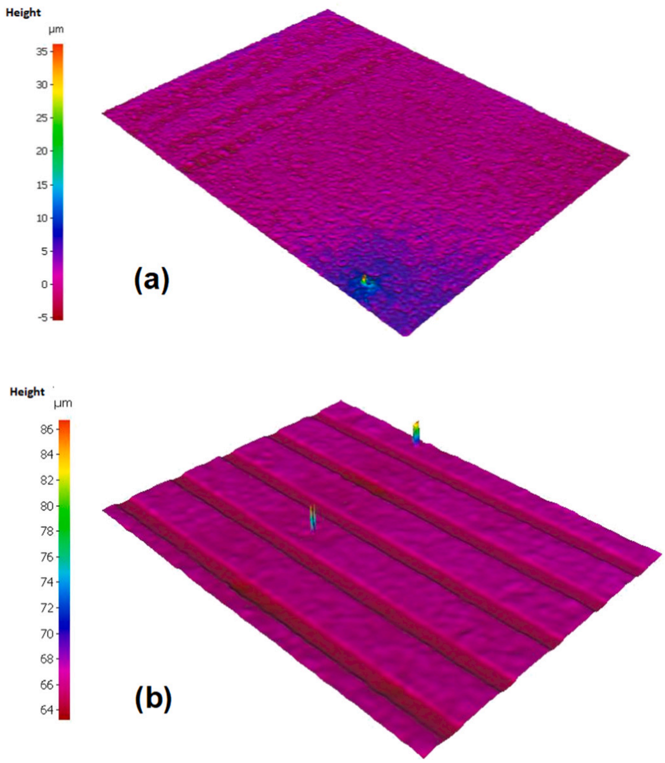

Fig. 8. 3D optical micrographs of cutting tools with textured surfaces: (a) untreated (NTT), and (b) laser treated (TPT) with α = 20%.

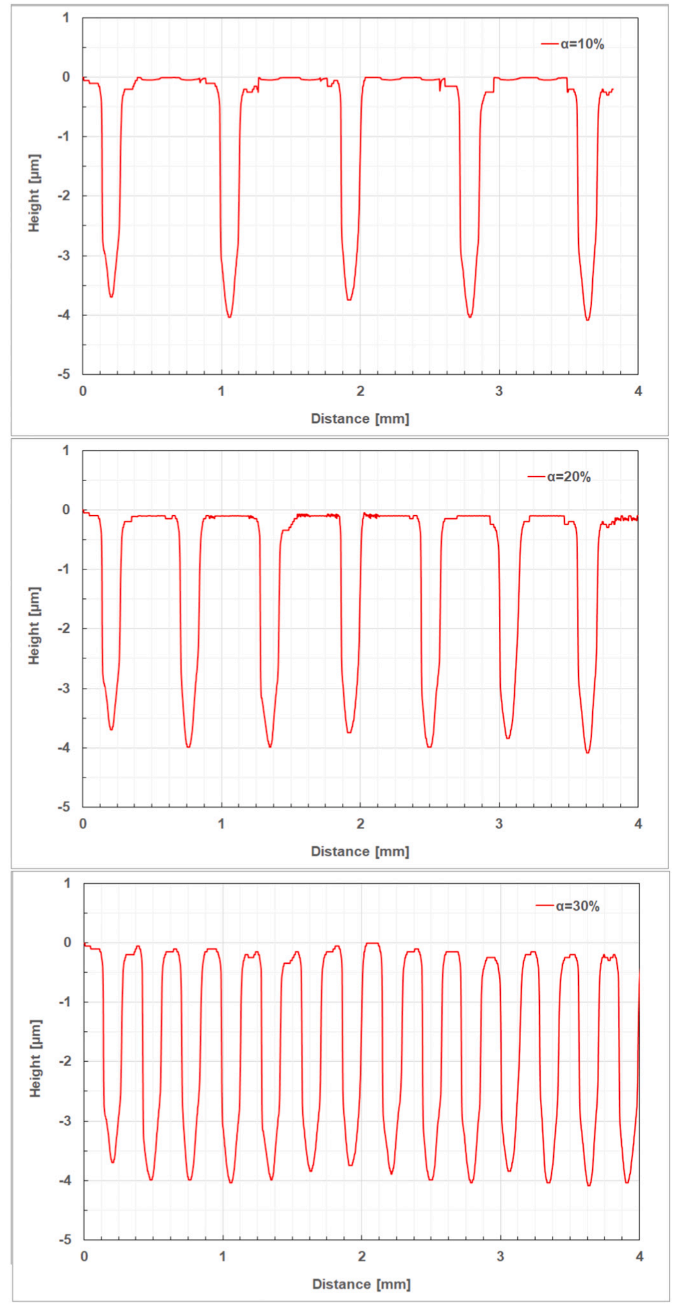

Fig. 9. 2D profilometer results of different micropatterns obtained for three different densities α.

more than 22%, indicating the best case, and improved the tool cutting surface lubrication. The CTT configuration was designed to improve efficiency under the machining stage under full lubrication conditions, and it showed the best performance in reducing friction. The NTT configuration performed worse than TTT and CTT in all conditions, showing that texture density is a critical parameter that should be considered for the texture design of non-conformal contacts. However, the cross configuration produced better results, probably because of the presence of several micro-cavities, which were more efficient at entrapping the lubricant at the intersection and facilitating chip debris removal.

3.4. Performance of machining tool

Figs. 17 and 18 show the experimental force measurements for the nontextured cutting inserts and those treated with the femtosecond laser with consideration of the lubrication process (complete or starved fluid lubrication conditions). Titanium was machined during the minute under cutting conditions at a rotational speed of 160 m/min. The three components of the cutting force were the axial thrust force (F_x), radial thrust force (F_y), and main cutting force (F_z). The experimental cutting force versus the time curves show that the recorded values were stable and constant during the cylindrical turning operation under the machining conditions with full lubrication (see Fig. 17). Under the same cutting conditions, it was clear that microtexturing enabled the force values to be reduced by 20%.

Meanwhile, in starved lubrication machining, the cutting force values of the cutting inserts with smooth inserts remained constant in the interval between the first 30 to 40 s; subsequently, they started to increase slightly (see Fig. 18). However, those with textured cutting inserts showed a significant increase after 30 s and then rapidly reached a second, higher, and relatively stable tray (see Fig. 18(b)).

Under the same conditions, the cutting force values were found to be more important with non-textured tools than with the coated textured tools because the micro-textures on the rake face reduced the tool–chip interface contact length, and the usage of lubricant minimised the friction between the tool and chip interfaces, thereby reducing the heat generated during machining.

However, the cutting force increased rapidly after 30 s for the textured inserts under severe conditions because it was quickly destroyed or even filled with chips. When the machining stage occurred under full conditions, the same micro-textures enhanced the material grip and helped the cutting inserts to reduce the cutting forces from 20% to 25% and (see Figs. 17 and 18).

Kawasegi et al. [9] showed that the variation in cutting forces estimated during the turning stage using multiple patterns can be attributed to the contact lengths between a chip and a textured rake face. Moreover, Zhou et al. [10] investigated the combined effect of using grooves on a micrometric scale and good lubricating conditions on the

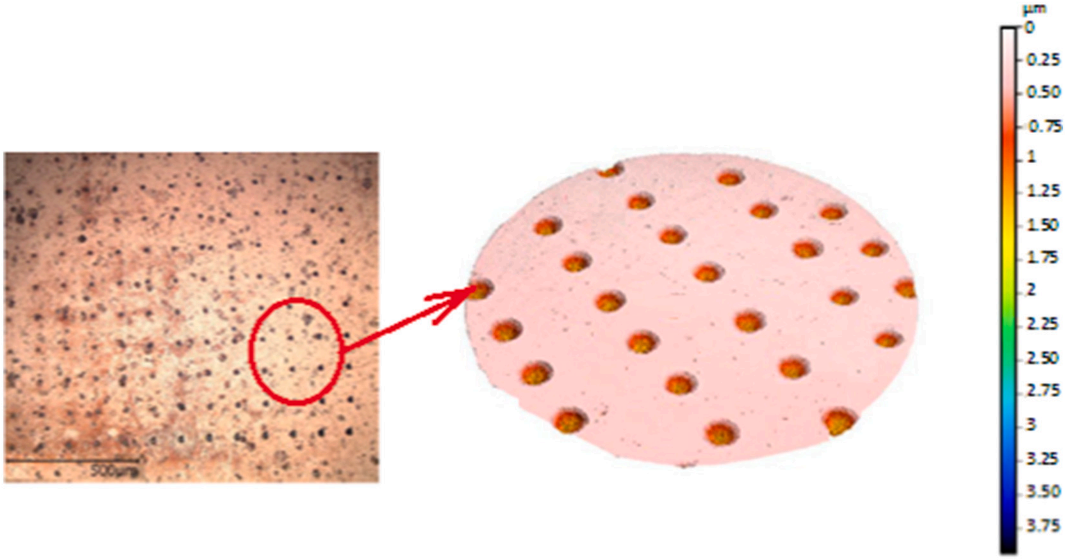

Fig. 10. 3D optical micrographs of tool surface with micro-dimples treated using a femtosecond laser.

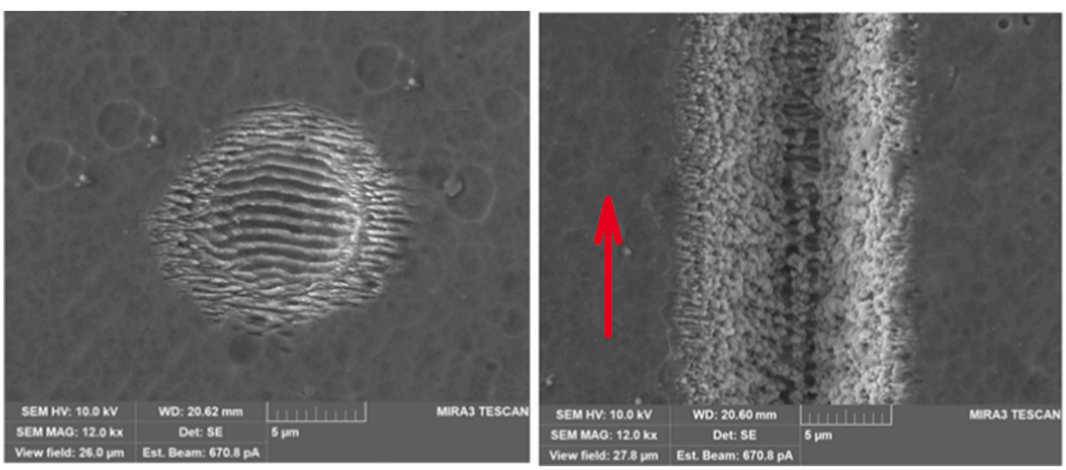

Fig. 11. SEM images of (a) craters generated by femtosecond laser ablation at 1 kHz, 0.05 J.cm^{-2} and 50 pulses (b) grooves structures produced at 100 Hz, 0.5 J.cm^{-2} and 5 mm/s using one pass.

machining efficacy of uncoated tools when milling titanium alloys. Their results indicated that, compared with using conventional tools and cutting fluids, a significant decrease in the cutting force by up to 38.4% and a cutting tool wear rate of up to 63.3% were obtained when using optimal microgroove textured tools and nanofluids. Fig. 19 shows the evolution of the three components of the cutting tool force values measured at cutting speeds varying from 40 to 200 rpm during the turning operation, where laser treatment (with smooth or textured cutting inserts) and lubrication process conditions (with complete lubrication or starved lubrication) were considered. The average force values presented on these graphs and error bars were obtained from six repeated tests over time. The error bars in the graphs correspond to the dispersion of the experimental data. The average force values measured on the textured cutting inserts were significantly lower than those measured on the untextured cutting inserts. This difference was minimal for reducing cutting speeds of 40 and 80 m/min. However, the improvement in the cutting characteristics of the coated and untextured tools was not as substantial, with a reduction of only 2% to 8% under starved lubrication.

The cutting speed affected the cutting force of the cutting inserts. The cutting behaviour of TPT micro-textured tools decreased by 28% to 45%, whereas those measured on PTT tools decreased by 21% to 38% compared with those of the smooth NTT tool under complete fluid lubrication. However, under starved fluid lubrication under the same conditions, these force values decreased by 7% to 10% in TPT micro-textured tools and 6% to 8% in PTT micro-textured tools. It was observed that the shape and orientation of the patterns on the micrometric scale significantly affected the cutting force values. They were the smallest for the CTT cutting insert tools. It was clear that the grooves on the micrometric scale considerably reduced the average cutting forces during the turning phase. This was shown for all the cutting speeds used in this study. The cutting force measured during machining on the TTT and CTT tools reduced significantly under complete fluid lubrication by 31% to 48% and 34% to 50%, respectively, and by 8% to 10% and 9% to 12% under starved fluid lubrication, respectively. Wang et al. [22] showed that under boundary lubrication conditions, shallow micro-structures reduced friction, probably owing to the squeeze effect.

A study to compare the performances between structured and un-textured machining inserts was conducted by Lei et al. [23]. They concluded that cutting force values decreased by 10%–30% when micro-pool lubrication conditions were applied. The experimental results showed that the efficacy of the textured cutting inserts improved

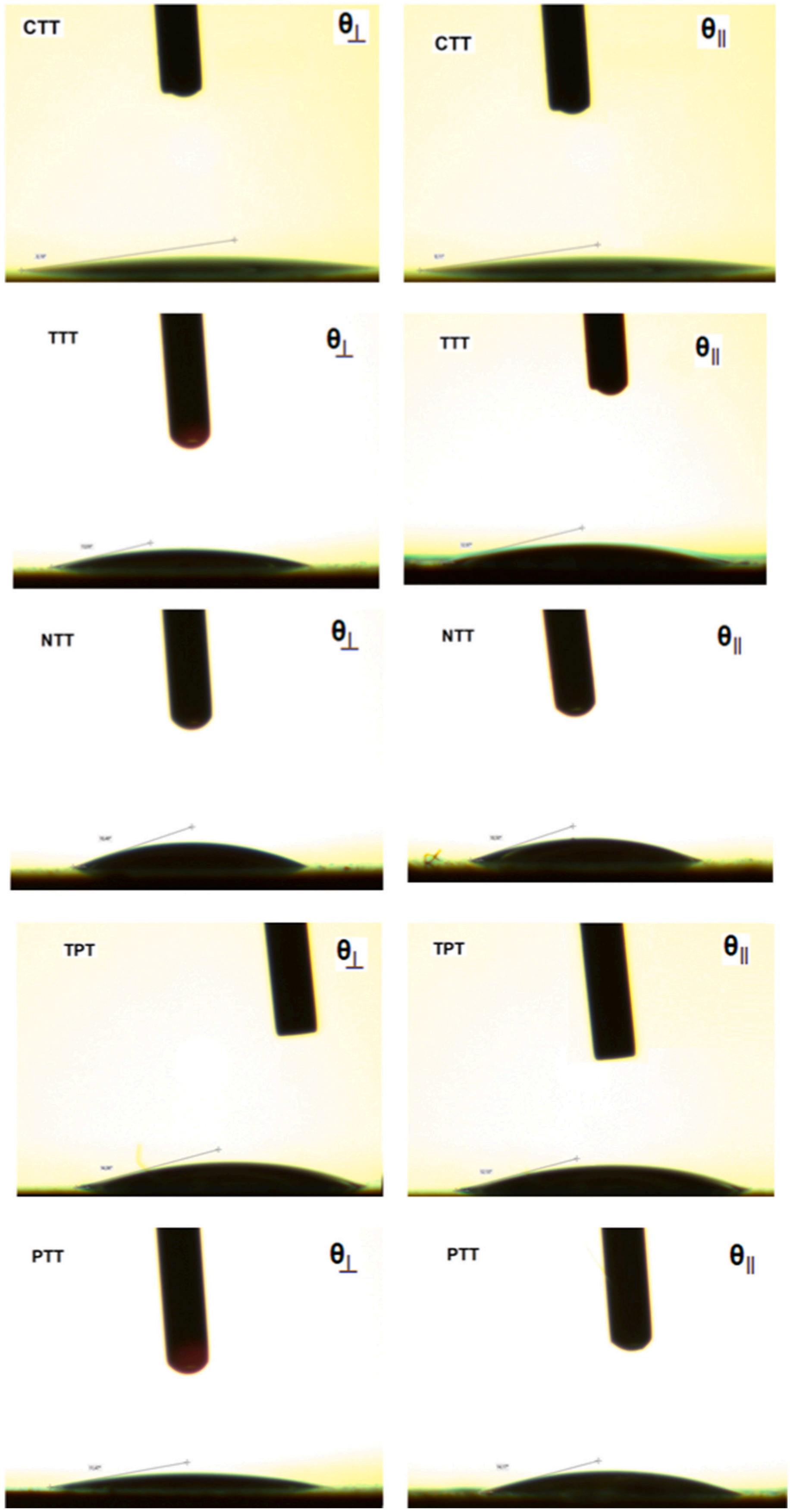

Fig. 12. Photographs of static fluid lubrication contact angle measured using micro-textured cutting surfaces in both perpendicular and parallel directions (area density: 30%).

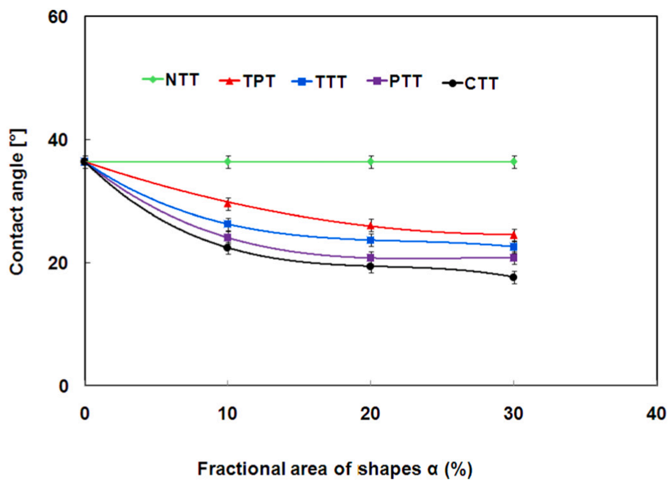

Fig. 13. Variation in water droplet contact angles on templated coated cutting areas with or without textured surfaces based on different fractional areas (area density: 10 to 30%).

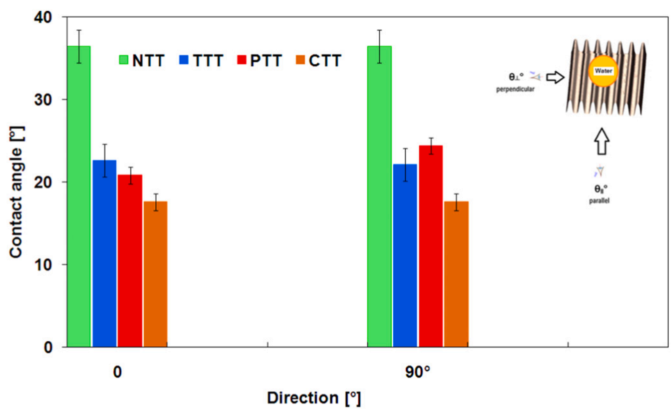

Fig. 14. Evolution of water droplet contact angles in both directions with or without textured surfaces with coating: (a) parallel direction, and (b) perpendicular direction (area density: 30%).

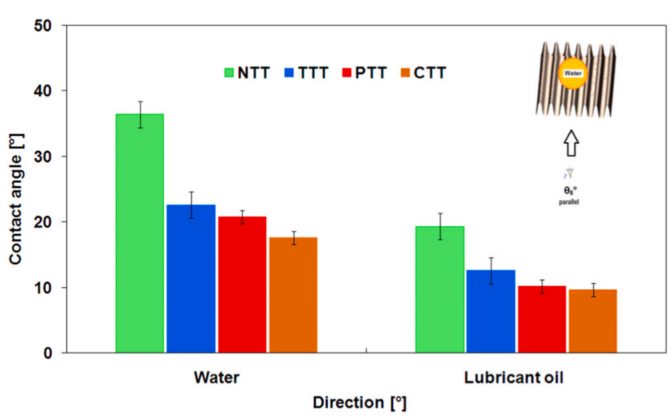

Fig. 15. Summary of contact angle data: (a) water droplet contact angles, and (b) oil lubrication droplet contact angles on different coated micro-textures areas (area density: 30%).

significantly, particularly under complete lubrication conditions. Wu et al. [4] reported that the presence of lubricant within textured cavities considerably reduced the cutting forces and increased the cutting tool life simultaneously. Arulkirubakaran et al. [24] confirmed that using

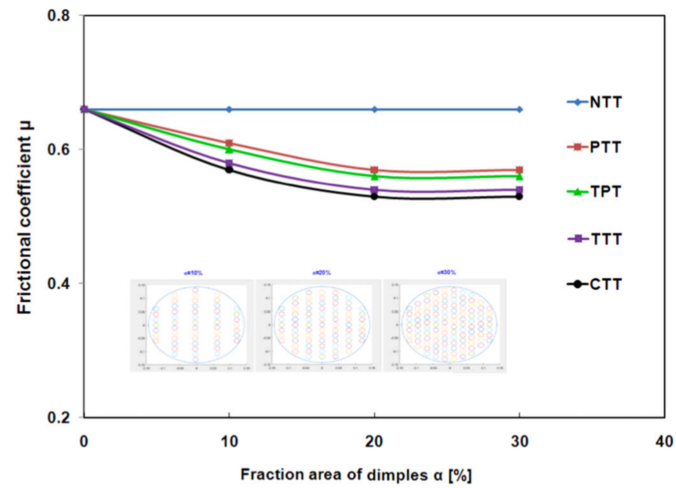

Fig. 16. Fractional area effect of micro-patterns vs. friction coefficient (area density: 10 to 30%).

different types of texture patterns on the rake face of the coated (TiN and TiAlN) and uncoated cutting tool inserts can reduce the detrimental effects that occur during the machining of Ti6Al4V. Otherwise, it was found that the cutting force and temperature were found to be at a minimum during the machining of Ti6Al4V alloy with a TiAlN-coated perpendicular textured tool using the wire-EDM process. Under the machining conditions chosen in our study, we observed the improved performance of cutting tools with CTT cutting inserts; —in this case, the cutting force—was moderately the weakest when machining with a cutting tool coated with TiAlN and textured by a femtosecond laser.

3.5. *Tribological attitude of cutting insert–workpiece contact*

Fig. 20 illustrates the graphical evolution of the friction coefficient values versus the cutting speed values, measured at the cutting-insert–workpiece contact for different microstructured cutting tools (NTT and CTT) and various lubrication processes (complete and severe lubrication conditions).

It is clear that the friction coefficient decreased in the complete lubrication condition, as illustrated in Fig. 20(a). The friction coefficient value of the CTT cutting tools decreased by 14%–23% compared with that of the NTT. However, Fig. 20(b) shows that the microtexturing of the smooth area of the tool improved the tribological behaviour of the machining tools via their frictional properties compared with the smooth cutting tools. Obikawa et al. [25] indicated that the friction coefficient and force values decreased significantly when microdimpled and parallel surface textures were used. The tribological performance of micro-textured surfaces is directly related to viscosity and geometrical aspects, as reported by Wang et al. [22] and Braun et al. [26].

Cutting insert wear investigations were conducted on all the inserts after turning using optical microscopy to measure and examine the wear mechanisms on the rake face. Fig. 21 shows optical images of the rake face of the cutting inserts after turning for 150 mm, suggesting that the micro-textures still existed and were not completely buried by the adhesions of the workpiece material. However, we can also observe a negative shape deviation on the rake faces, which can be connected to the cutting insert material loss owing to the few flank wear. In addition, no signs of substantial crater wear were observed. Therefore, placing the textures close to the cutting edge helped decrease tool wear and improve the performance of cutting tools during machining. This parameter will be considered in our subsequent experimental study.

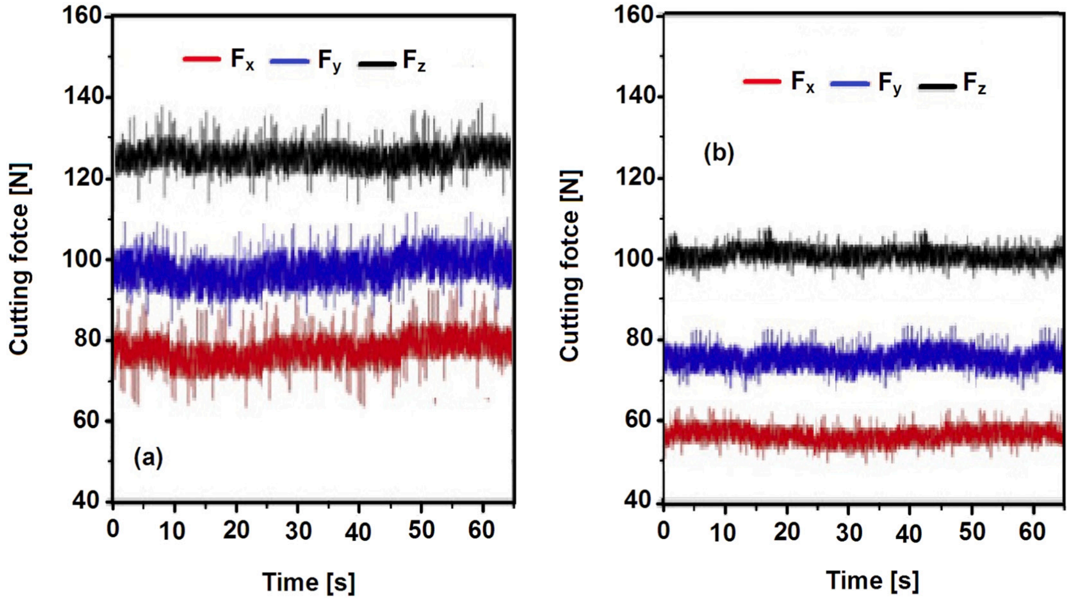

Fig. 17. Evolution of cutting forces vs. time at cutting velocity of 160 m/min in complete lubrication: (a) untextured cutting surface (NTT), and (b) textured cutting surface (CTT) (area density: 30%).

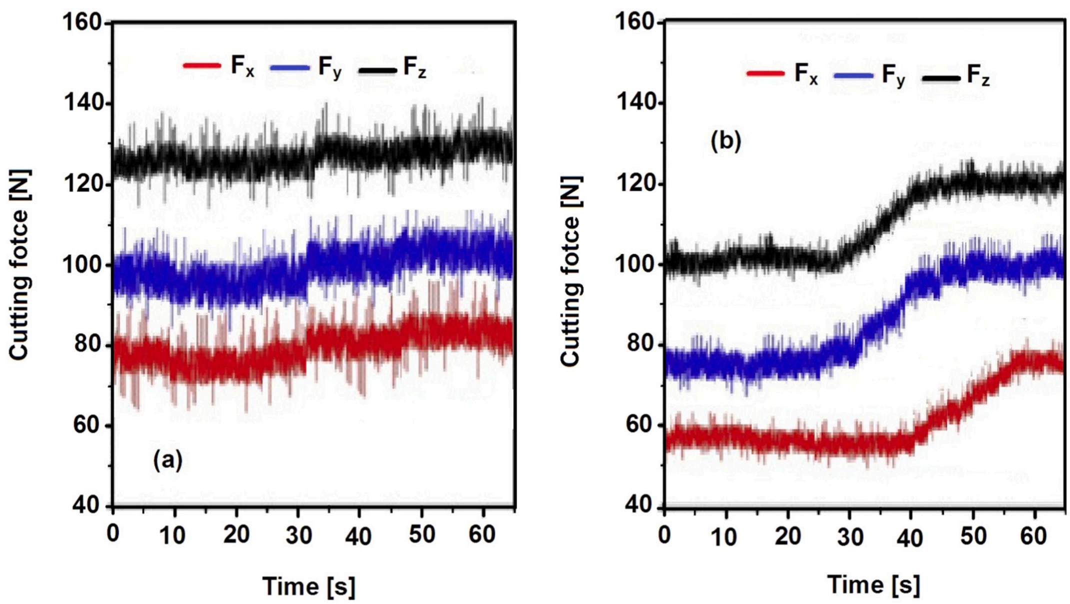

Fig. 18. Evolution of cutting forces vs. time at cutting velocity of 160 m/min in starved lubrication: (a) untextured cutting surface (NTT), and (b) textured cutting surface (CTT) (area density: 30%).

4. Conclusion

In this study, micropatterns of different geometries and sizes were fabricated on the rake of cutting tools using femtosecond laser equipment to study their effect on cutting tool performance and life in turning experiments during titanium machining. The large microstructured patterns were controllable on the cutting tool areas using a laser. The findings of this study are as follows.

- Femtosecond laser treatment induced surface roughness, which enhanced the hydrophilicity and oleophobicity of the final cutting surface.
- Cutting inserts with surface crossed micropatterns (CTT) indicated a larger decrease in cutting force and friction coefficient values compared with untextured tools (NTT).
- The CTT significantly increased the lubricity with improved cutting fluid retention in the cutting insert area.
- Microgrooves on the rake face resulted in reduced wear, thereby improving the tribological performance. The wear efficacy of these pretreated cutting inserts (CTTs) differed from that of the untextured inserts (NTT).
- The cutting tool performance in cylindrical machining improved significantly owing to microtexturing, which served as a micro-dimple and ensured stable lubrication.
- Textured patterns with crossed grooves (CTT) were more efficient in increasing the tool life than all other grooves, regardless of whether

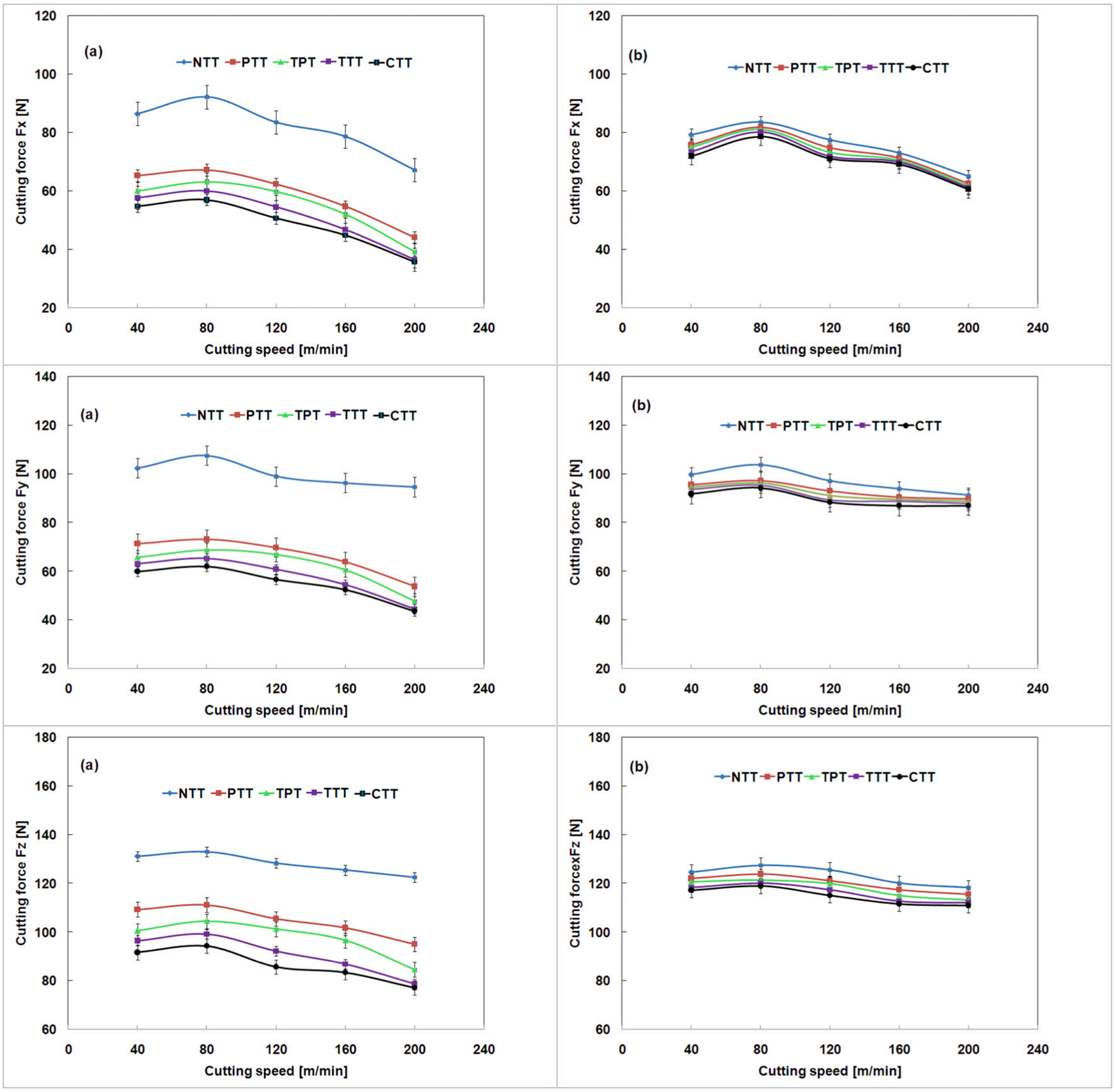

Fig. 19. Evolution of cutting force values Fx, Fy, Fz measured on machining cutting inserts at various cutting speeds and under (a) complete fluid lubrication and (b) starved fluid lubrication (area density: 30%).

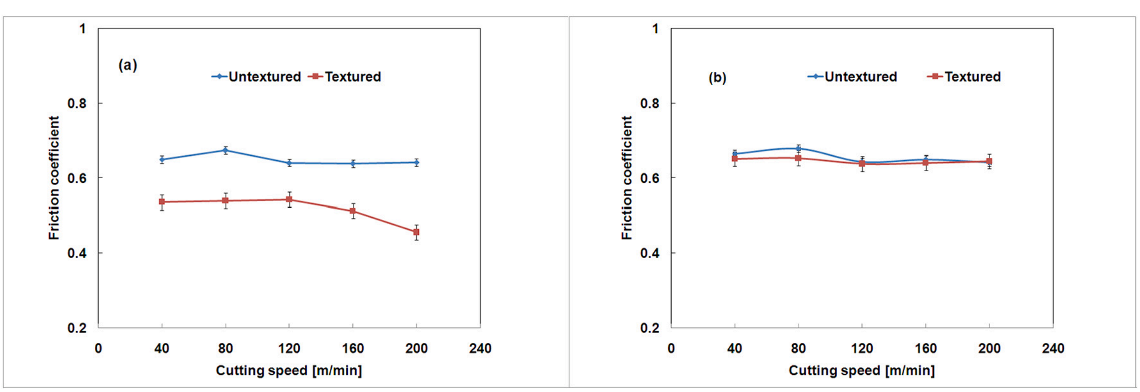

Fig. 20. Tribological behaviour at the cutting-insert–workpiece contact of TPT tools compared with those of NTT tools at various cutting speeds and under (a) complete and (b) starved lubrication (area density: 30%).

they were oriented perpendicularly or parallel to the chip movement and irrespective of the dimples being distributed uniformly.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

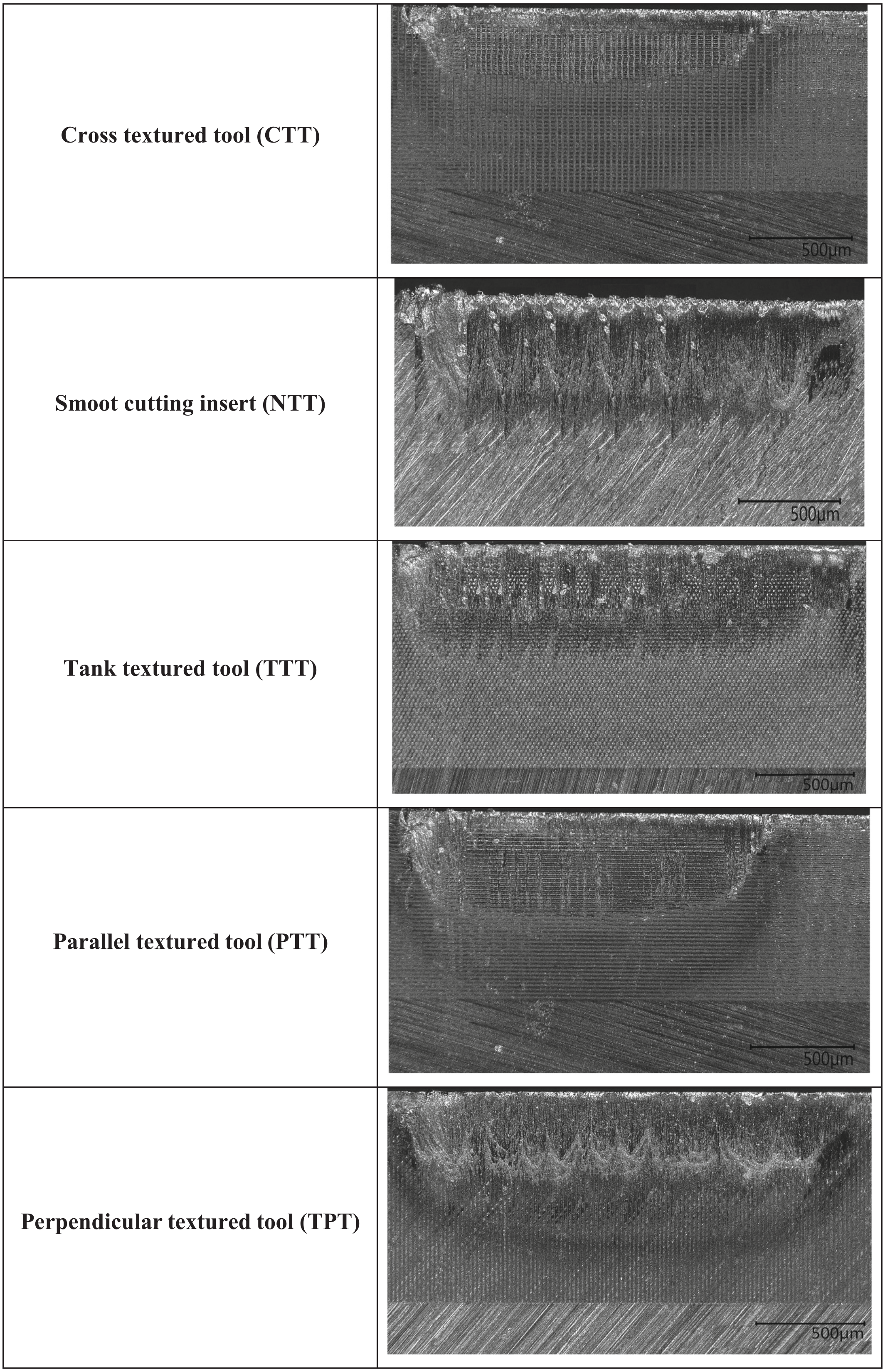

Fig. 21. Optical images of the rake faces after cutting stage under complete lubrication (cutting speed: 200 m/min, area density: 30%).

the work reported in this paper.

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Glossary

CTT: cross textured tool
NTT: smooth original cutting insert
PTT: parallel textured tool
TPT: perpendicular textured tool
TTT: tank textured tool
Ti6Al4V: titanium alloy
TiAlN: titanium–aluminium–nitride
WC/Co: tungsten–carbide cobalt