

Surface texturing of cutting inserts for turning of aluminium – Study of cutting forces, wear, chip formation and tool-chip contact

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Surface texturing of cutting inserts for turning of aluminium – Study of cutting forces, wear, chip formation and tool-chip contact

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Abstract

This paper presents wet machining of wrought aluminium alloys with textured and non-textured tools. To improve the machining performance, textures were produced on rake face of uncoated cemented carbide by using femtosecond laser machining. Experiments were conducted on a computer numerical controlled lathe with each textured tool and then compared to conventional cutting tool. To evaluate the cutting performance of tested tools, the following criteria were considered: cutting forces evolution, rake face wear, flank face wear and chip formation. In parallel, simulations based on boundary elements method (BEM) were used to analyse the local effects of the texture in the contact. A significant decrease of flank wear about 90% is observed with textured tools with nanometric Laser Induced Periodical Surface Structures (LIPSS) and of 80% with double-scale structure (LIPSS + Dimples). Double-scale structured tool presents a lower cutting force in comparison with conventional cutting tool. An increase of shear angle value with tool textured with micrometric structure (Lines) is observed. A lower height of adhesion on rake face of the tool with LIPSS compared to other tested tools is found too. These results constitute another step in the purpose to design a new generation of tools for precision turning of aluminium alloys.

Keywords: Femto-second laser; Surface texturing; Tungsten carbide tool; Turning; Wrought aluminium alloy; Cutting performance.

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1 Introduction

Aluminium materials, in the form of cast or wrought alloys, are employed in a wide variety of applications especially in transportation industry. They are known for their high ductility and low melting point. Despite their good machinability, wrought aluminium alloys with copper adhere strongly on cutting tools during machining, which can lead to tool breakage [1]. Nowadays, surface structuring can be used for improving cutting inserts by adapting their tribological and physicochemical properties. Different techniques have been used by several authors for altering the surface topography of cutting tools. Kim et al. [2] used Micro Electro Discharge Machining for texturing CBN inserts for dry turning of stainless steel. Obikawa et al. [3] used chemical etching for texturing coated cemented carbide inserts for aluminium orthogonal cutting. Furthermore, Stoeterau et al. [4] used picosecond laser technique for texturing cemented carbide inserts dedicated to aluminium and stainless-steel turning. Sugihara & Enomoto [5] used femtosecond laser technique for aluminium milling with coated cemented carbide inserts while Kawasegi et al. [6] used Focused Ion Beam for texturing carbide inserts for milling of aluminium. Most of research studies regarding cutting tool improvement focused on rake face structuring. Lei et al. [7] fabricated micrometric structures on uncoated cemented carbide rake face insert using femtosecond laser for machining mild steel. Several types of structures have been tested such as dimples for turning both aluminium and stainless steel [4], micro-grooves by Kümmel et al. [8] for stainless steel turning and nano-grooves for aluminium milling [5]. Several studies investigated the best orientation of structures from cutting edge and it was found that structures should be oriented in parallel direction to the cutting edge as observed for example by Sugihara & Enomoto [9] while turning aluminium with coated carbide inserts. For wrought aluminium alloy machining, rake face structuring has shown benefits in decreasing cutting forces, adhesion, roughness of machined surface, chip size in terms of length, width and curl diameter, concentration of aluminium atoms on the rake face of the cutting tool and in increasing shear angle. Durairaj et al. [10] reported that dimples type microstructures on the cutting tool rake face for orthogonal cutting of aluminium decreased cutting force, increased shear angle, and decreased thrust force, percentage concentration of aluminium on the rake face of the cutting tool and actual contact area by 7%, 9%, 16%, 51% and 61% respectively. Kawasegi et al. [11] found that nanostructures with low digging on the cutting tool rake face for turning of aluminium decreased cutting force, feed force and thrust force by 13%, 25% and 30% respectively. Yu et al. [12] investigated the roughness of machined surface using tools textured with micro-grooves in oblique, longitudinal and transversal orientation from the cutting edge. They reported that oblique texture decreased by 8% roughness of machined surface compared to non-textured tool for dry cutting of aluminium. They also reported an influence of texturing on chip morphology since they produced continuous chips with untextured tool and discontinuous chips with textured tools. Sugihara & Enomoto [9] reported a decrease of height of adhesion on rake face of textured tool with micrometric lines up to 77%.

In this study, we used femtosecond laser machining to create nanometric, micrometric and double scale (nano- + micro-) structures. We propose to investigate the effect of double-scale structure for aluminium turning, to estimate if such a preparation must be considered in the design of a new generation tool. Sugihara & Enomoto [5, 9] studied the effect of continuous double scale structure (Lines+LIPSS) in improving milling of aluminium while Kawasegi et al. [11] used this structure in improving turning of aluminium. Xing et al. [13] and Zhang et al. [14-15] used Lines+LIPSS in turning of stainless steel. Compared to the available literature, our new contribution is the characterization of the effect of a discontinuous double scale structure combining nano- and micro-scale on the flat rake face of uncoated cemented carbide tool. We aim to investigate if there is a synergy between these structures presenting two orders of dimensions. The cutting performance of each structured tool in wet machining of wrought aluminium alloy is studied compared to conventional tool.

Different analyses were performed including cutting force evolution, rake face wear, flank face wear and chip formation. In addition, the contact between the chip and the textured rake face has been modeled through a boundary element method software developed by the team and described in [16].

The analysis of the simulation could help better understand the behaviour by providing local pressures and real contact areas.

2 Experimental setup

2.1 Tool and tool-holder

The inserts used for this study were made of tungsten carbide with 6% of Cobalt binder (Seco Tools®, TPGN160304 F890). The average grain size of carbide is lower than 1 μm . These inserts are uncoated with flat rake face and no chip-breaker. It has zero rake angle and 11° clearance angle. An uncoated flat face geometry of inserts was chosen because it was interesting to restart the tool design from the beginning and to observe if the produced textures on their own can improve cutting, even without features dedicated to chip flow, chip breaking or tool life enhancement. Moreover, in this configuration, a femtosecond laser setup, permitting only to create structures on plane surfaces was sufficient. Inserts were mounted on CTGPR2020-16 tool holder (lead edge angle $\kappa_r = 91^\circ$, inclination angle $\lambda_s = 0^\circ$). Therefore, all presented tests in this article are in orthogonal cutting configuration. Lead edge angle not equal to 90° will slightly change the cutting width but will not affect the cutting configuration. Fig.1 shows the tool geometry and tool holder used for experiments.

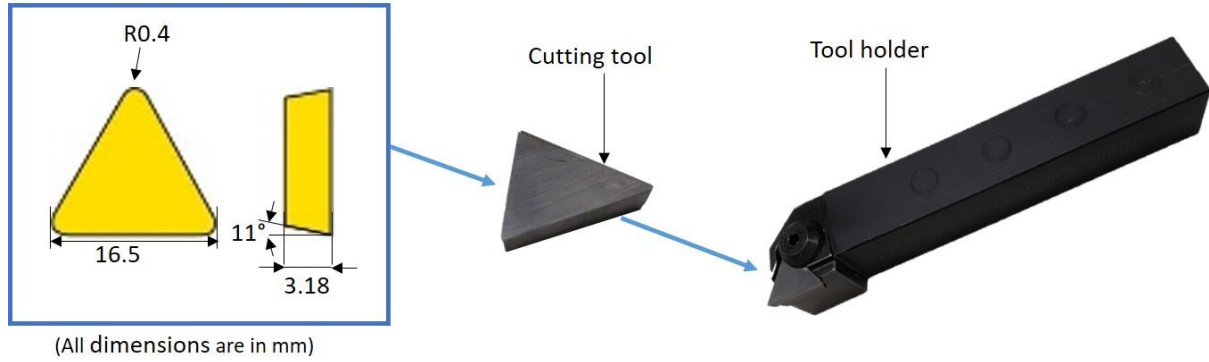


Fig. 1 Cutting tool and tool holder used for experiments

2.2 Femtosecond laser machining

The equipment used for creating structures was a femtosecond laser source (Tangor® HP model from Amplitude Systems®, France). It has an average power of 100 W, a maximum pulse energy of 500 μJ , a wavelength of 1030 nm and a variable repetition rate adjustable from 1 Hz to 2 MHz. The minimum pulse duration is equal to 400 fs. Three types of structures fabricated on flat rake faces are shown in Fig 2. Processing parameters in terms of applied fluence of laser and number of pulses (N) for generating nanometric and micrometric structures were previously investigated in a laser-matter interaction study Meliani et al. [17]. Three regimes were identified which correspond to: low interaction regime, LIPSS zone (Laser-Induced Periodic Surface Structure) and athermal ablation zone. LIPSS could be produced starting from $N=7$ at a peak fluence of 0.2 J/cm². Nanometric grooves named LIPSS have a depth of 225 ± 25 nm and a mean periodicity of 665 ± 25 nm (Fig. 2b). Double-scale structure was formed in two steps: firstly, LIPSS were fabricated and then dimples were produced. Dimples have a depth of 9 ± 0.2 μm , a diameter of 38 ± 2 μm and a period of 70 ± 2 μm (Fig. 2c). Micrometric lines have a depth of 9.5 ± 0.2 μm , a width of 65 ± 2 μm and a period of 150 ± 2 μm (Fig. 2d). Table 1 and 2 indicate both texture's density and volume rates definition and calculated values for each tested tool. These design specifications were employed according to previous results at the end of tribological tests on a linear tribometer. The purpose was to study tribological performances, both friction and wear, of structured surfaces at different dimensional scales. Tribological tests revealed that structures such as lines or lines+LIPSS were buried by aluminium. In addition, in term of time processing, dimples were faster to produce than lines. All structures were realized with a parallel orientation at a distance of 50 μm from the cutting edge. All inserts were

washed in an ultrasonic cleaner with ethanol for 5 min before and after the laser machining for removing debris.

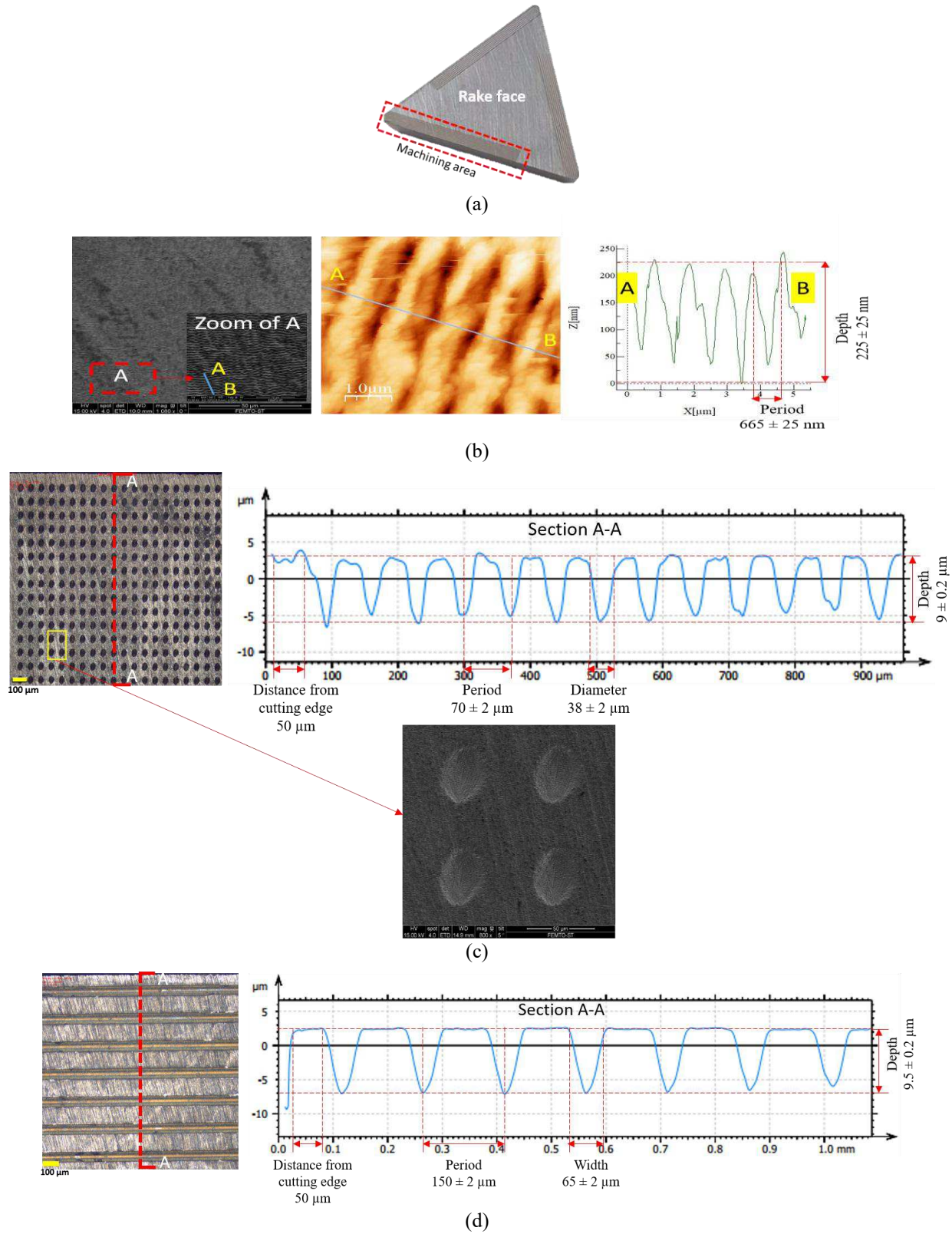


Fig. 2 a) Textured area on cutting insert, b) details of nanometric scale structure (LIPSS), c) details of double-scale structure (LIPSS+Dimples), d) details of micrometric scale structure (Lines)

Table 1 Texture's density and volume rates formulas

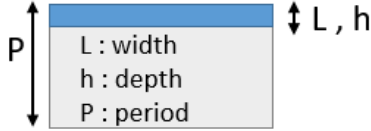
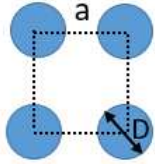
Type of structure	Texture density (%)	Volume rate ($\times 10^6 \mu\text{m}^3/\text{mm}^2$)
Lines or LIPSS 	$\frac{L}{P} \times 100$	$\frac{L \times h}{P}$
Dimples 	$\frac{\pi D^2}{4a^2} \times 100$	$\frac{3\pi D^2 h}{4a^2}$

Table 2 Texture's density and volume rates for textured tools

Type of structure	Texture density (%)	Volume rate ($\times 10^6 \mu\text{m}^3/\text{mm}^2$)
LIPSS	90	0.23
LIPSS+Dimples	23	6
Lines	43	4

The four textures (Fig. 3) have been measured using a Bruker white light interferometry profilometer. The obtained topographies are shape-corrected using a plane-fit model and a gaussian filter is applied to avoid acquisition's artefacts.

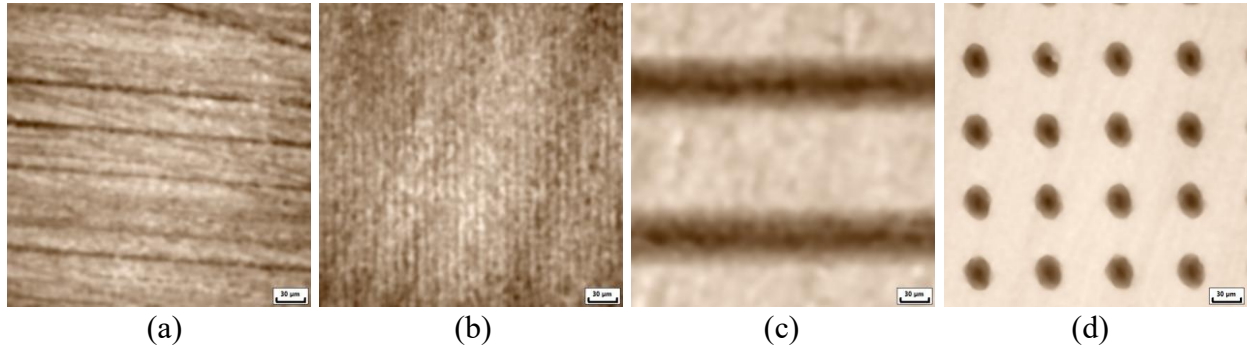


Fig. 3 0.3 mm x 0.3 mm topographies of (a) non-textured ($S_z = 1.68 \mu\text{m}$), (b) nanometric grooves ($S_z = 1.01 \mu\text{m}$), (c) micrometric grooves ($S_z = 15.29 \mu\text{m}$) and (d) double scale textures ($S_z = 12.18 \mu\text{m}$) obtained by white light interferometry

2.3 Cutting experiments

Turning tests were performed on a Doosan Lynx 220Y, a 4-axis CNC lathe with a maximum spindle motor power of 15 kW and a maximum spindle speed of 6000 rpm. Three textured tools presented in Fig. 2 were tested and compared to initial cutting tool. As cutting material, round bars with diameter 80 mm of aluminium alloy 2017A were used. The choice of wrought aluminium alloy 2017 as machined material is based on numerous studies already available in literature and presenting tool wear results. Therefore, obtained results in our study could be easily compared to this data. Table 3 lists the chemical composition of aluminium alloy 2017A. Cutting experiments were conducted in wet lubrication mode using straight oil (Castrol® Carecut ES-2) which has a density at 20°C less than 1000 kg/m³ and a viscosity at 40°C of 8.8 mm²/s. Based on insert manufacturer specification and preliminary cutting tests, following cutting conditions were used: cutting speed $V_c = 485$ m/min, feed $f = 0.2$ mm/tr, depth of cut $a_p = 1$ mm. All cutting conditions (V_c, f, a_p) are kept constant during this

study. Cutting forces were measured by a dynamometer (Kistler® 9129 AEO) connected to a multichannel amplifier (Kistler® 5070). Cutting tests were repeated on conventional cutting tool and were reproducible.

In this experimental study, tested tools were used for different durations considering end-of-test criteria. Sharp increase of cutting forces and/or winding chips around the machined piece were parameters considered as end-of-test criteria for cutting tools. Table 4 gives duration of cutting experiment for each tested tool. Durations for non-textured tool and micro-textured tool represent the end-of-test period when tools were not usable anymore because chips were constantly winding around the machined piece. These durations are repeatable for each tool and allow us to perform reliable comparison between all tested configurations. Tools textured with nanometric grooves and double-scale structure were used for 330 seconds but they could be used for more time. The tool-life of non-textured tool could appear to be very low as a reference, but the geometry of the tool is simple (no chip-breaker, zero rake angle, non-coated) and then the reference tool life is here much lower than the ones basically observed in industry.

After cutting tests, rake faces of inserts were examined using a scanning electron microscope (SEM-FEI Quanta™ 450 W) and an optical microscope (Alicona Infinite focus®). The flank wear of worn inserts was analysed using a numerical microscope (Keyence® VH-ZST). Produced chips were characterized by measuring their thickness using a digital Vernier calliper with a resolution of 1 µm and a repeatability of about 10 µm.

Table 3 Chemical composition of the workpiece material aluminium alloy 2017A in wt.%

Element	Si	Mn	Cr	Cu	Fe	Mg	Zn	Al
Percent weight	0.2-0.8	0.4-1	0.1	3.5-4.5	0.7	0.4-1	0.25	remain

Table 4 Cutting durations for each tested tool for turning aluminium alloy

Type of structure	Non-textured tool	LIPSS (nano-)	Lines (micro-)	LIPSS+Dimples
Cutting time T_c (s)	70	330	40	330

2.4 Numerical model

The textured tool-chip interface has been modelled using a homemade boundary element method. Its objective is to compare the distribution of stress and deformation on the rake face and to analyse the behaviour of the chip. This software has been initially developed by Luc Carpentier for the tribology research field [16]. The simulation conditions summarized in Table 5 are given by the materials providers. They correspond to classical indentation conditions and do not consider the thermal softening and stress field caused by the cutting process. This simulation programme uses a coupled elastic-pressure truncation model to estimate contact conditions more quickly than a plasticity model would [18]. The threshold has been set to 750 MPa according to the estimated hardness of aluminium.

Table 5 Model parameters for static contact

Tool Young's modulus (MPa)	Chip Young's modulus (MPa)	Pressure threshold (MPa)	Chip geometry
750 000	74 000	750 MPa	Plane

The indent used in this case corresponds to the textured surface and the plane substrate represents the chip. For each topography of Fig. 3, there are three different applied forces to represent the evolution of pressure along the rake face. These pressures have been estimated using the cutting force (F_c) measured during machining tests and the real area of contact on the rake face (S_c) described in Eq. 1.

$$P_{app} = \frac{F_c}{S_c} \quad (1)$$

The mean value of P_{app} , defined from the machining tests and noted P_{mean} , is around 300 MPa for all the textures. According to Zorev's model [19], the max pressure on the rake face can go up to $3 \times P_{app}$ as the Fig. 4 shows a stress profile. So, the chosen pressure for the simulation will start just below P_{mean} at 250 MPa and will go up to 1000 MPa. An arbitrary pressure of 500 MPa is chosen to observe intermediate tendencies.

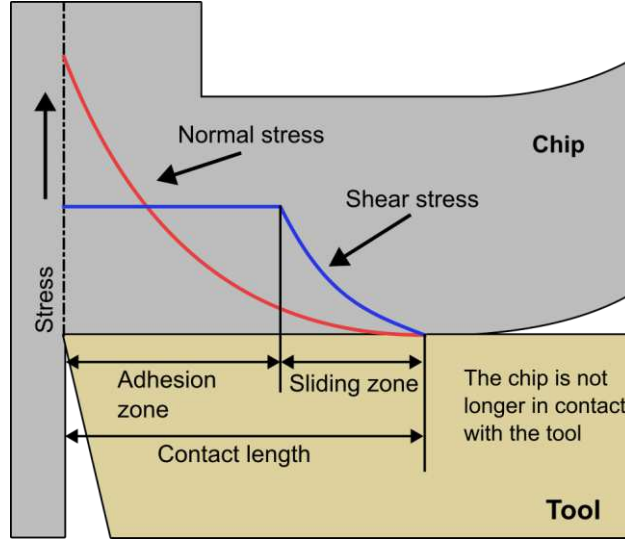


Fig. 4 Normal and shear stress on the rake face according to Zorev's model [19]

The calculations are driven by the applied force in simulation (F_{sim}), calculated by the following equation:

$$F_{sim} = \frac{P_{mean}}{S_{topo}} \quad (2)$$

where $S_{topo} = 0.09 \text{ mm}^2$ is the projected surface of the topographies.

This gives 22.5, 45.0 and 90.0 N for F_{sim} . The results from the Fig. 5 show the mapping of actual contact (b) and vertical gap under load in elastoplastic conditions (c). They also include data from the contact, such as the actual mean pressure (P_{real}), the actual contact area (S_{real}) and the ratio of the actual contact surface to the total surface (R).

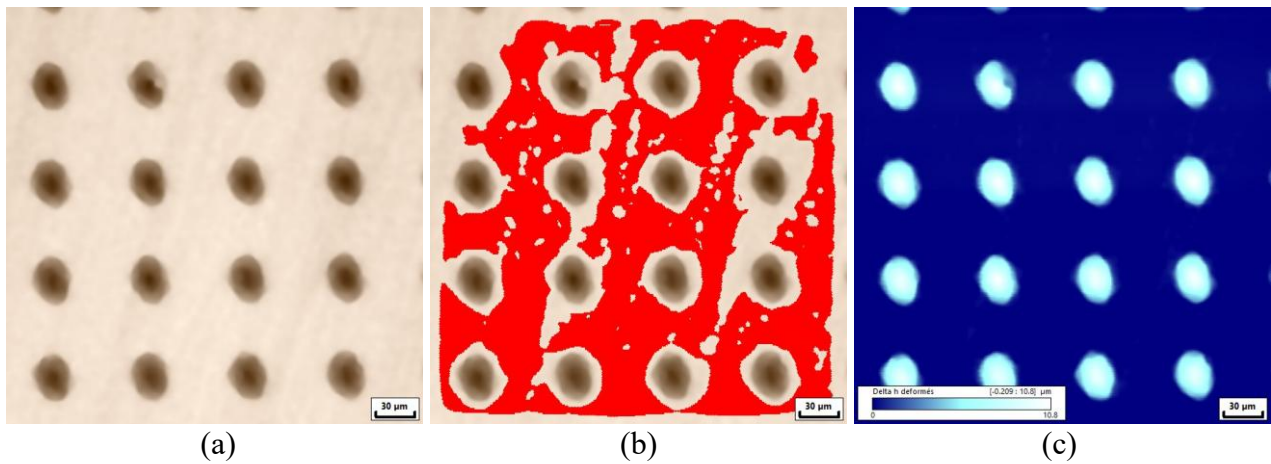


Fig. 5 Data processing on 0.3 mm x 0.3 mm topographies with (a) topography (b) actual contact area and (c) the distance between the indenter and the substrate under load

3 Results and discussion

3.1 Machining forces

The cutting force F_c and the feed force F_f were measured during cutting experiments. Thrust force was not considered because of the configuration of tests (orthogonal cutting). The values of force components were determined by the difference between the signals average during cutting and the signals average during non-cutting as shown on Fig. 6.

Fig. 7 compares mean cutting force (F_c), mean feed force (F_f) and the ratio F_f/F_c of non-textured and textured tools when turning aluminium alloy. Error bars presented on data show the variability of the stated mean value. The results indicate that cutting force is similar between the non-textured tool and tools textured with nanometric grooves (LIPSS) and micrometric grooves. A cutting force reduced by 6.9% is observed for the tool textured with double-scale structure. The feed force increases for all textured tools compared to non-textured one. For the initial tool, feed force is equal to 41 ± 1 N whereas for textured tools with nanometric grooves (LIPSS), micrometric grooves, double-scale structure (LIPSS+Dimples), feed force is equal to 88 ± 12 N, 48 ± 1 N and 53 ± 1 N respectively. The ratio F_f/F_c is greater for textured tools compared to non-textured tool. A part of contact area between rake face and chip is an aluminium/aluminium contact, which is likely to modify the friction conditions and the feed force. It can be a factor which explains greater values of feed force.

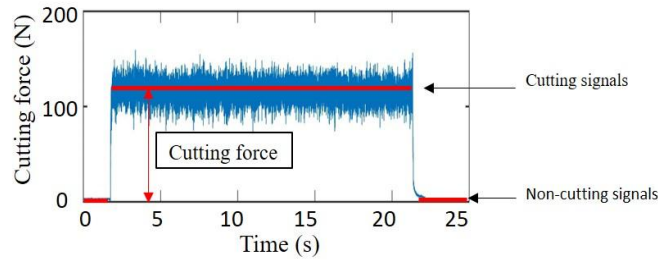


Fig. 6 Cutting force signal and representation of reference levels

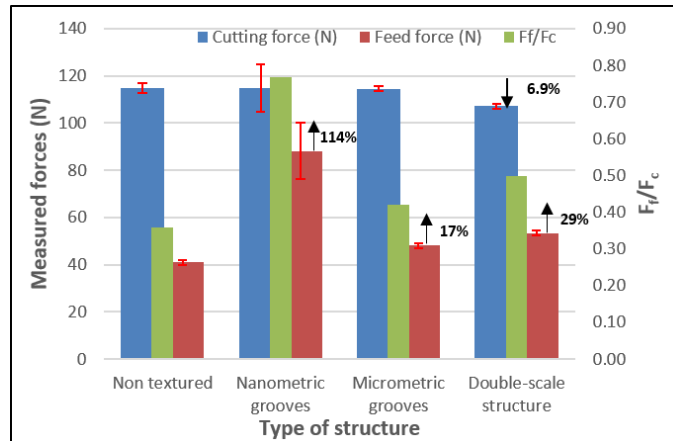


Fig. 7 Average values of cutting force and feed force for non-textured and textured tools

3.2 Flank face wear

After cutting tests, flank wear was characterized according V_b criteria defined in ISO norm NF3685. Six measurements of width V_b were noted as shown on Fig. 8. Since flank face is in contact with final machined surface, it is important to have minimum wear on this face. Table 6 presents flank wear data for textured and non-textured tools. Since period of machining is not similar between the four tested tools and to have comparable values of flank wear width for each tested tools, flank wear width per minute for textured and non-textured tools is plotted and presented on Fig. 9. Flank wear width evolution related to cutting time is assumed linear. In fact, no rapid degradation or cutting-edge degradation was observed during our tests. Therefore, we assumed to be in a linear zone. Error bars show the variability between six measurements of V_b for each tested tool.

Textured tools with nanometric structure (LIPSS) and double-scale structure (LIPSS+Dimples) reduce flank wear width by 91.5% and 79.7% respectively compared to a non-textured tool. Whereas tool with micrometric grooves increases flank wear width compared to a non-textured and non-coated tool. So, rake face structuring has an influence on controlling flank face wear. This assessment is relatively new, only Zhang et al. pointed out experimentally a link between rake face structuring and flank wear control when structuring a coated tool rake face for stainless steel cutting but without giving any explanations [14].

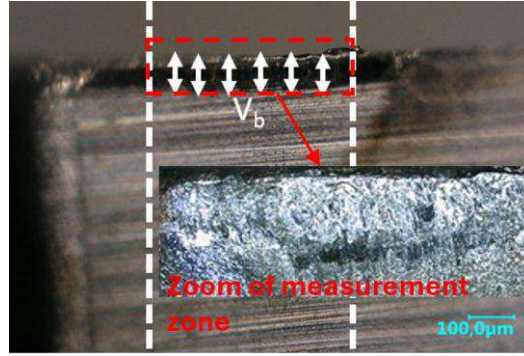


Fig. 8 Measurement of flank wear

Table 6 Average flank wear as a function of cutting durations for each tested tool

Type of structure	Non-textured tool	LIPSS (nano-)	Lines (micro-)	LIPSS+Dimples
T_c (s)	70	330	40	330
V_b (μm)	67	27	111	64
V_b rate (μm/min)	57.7	4.9	166.7	11.7

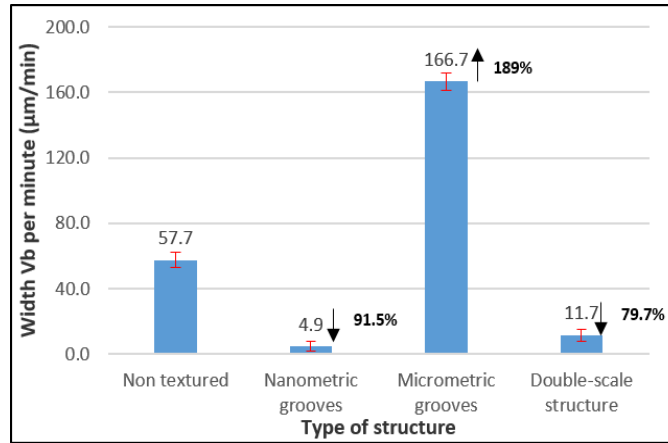


Fig. 9 Average flank wear per minute for non-textured and textured tools

3.3 Rake face wear

Fig. 10 shows SEM images of non-textured and textured tools rake faces after cutting tests. These images reveal that there is adhesion of aluminium on rake faces. Microtextures namely lines and dimples were buried by aluminium and LIPSS were destroyed. Fig. 11 presents 3D images and average 2D profiles of worn rake faces realized according to major direction of chip flow along cutting edge. Average profiles were extracted from 1366 profiles made from 3D surfaces for all tested tools except tool textured with LIPSS+Dimples (discontinuous structure) where presented profile is one that is the most representative of worn rake face. The average profile of non-textured tool rake face shows a high adhesion situated from 250 to 500 μm from the cutting edge and reaching a height of adhesion of 3 μm. While a lower adhesion on the tool textured with LIPSS is observed near cutting edge till 300 μm with a maximum height of adhesion of 1.5 μm. Regarding tool textured with

micrometric grooves, first lines were buried until 400 μm from cutting edge. Concerning tool textured with LIPSS+Dimples, an adhesion area is observed from 250 μm until 500 μm from cutting edge. An additional test done with a structured cutting tool with LIPSS, Fig. 12 shows rake face of tested tool after aluminium turning. No built-up-edge (BUE) against rake face of cutting tools was observed neither on non-textured tool nor on textured tools. After examination of the different tested tools, adhesion wear occurred without forming built-up-edge. Therefore, among all tested tools in this study, nanometric structure shows anti-adhesive properties when machining aluminium alloy.

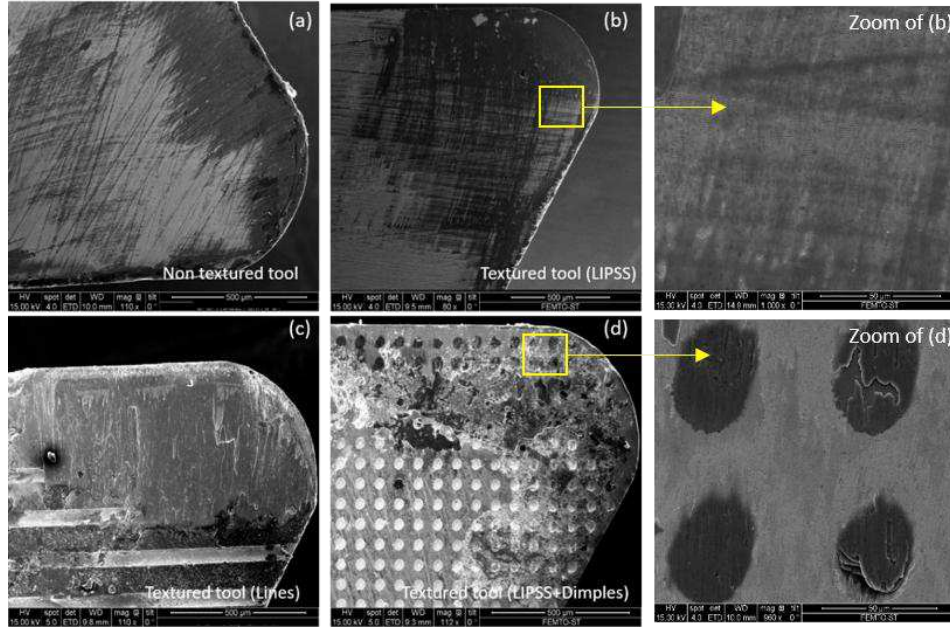
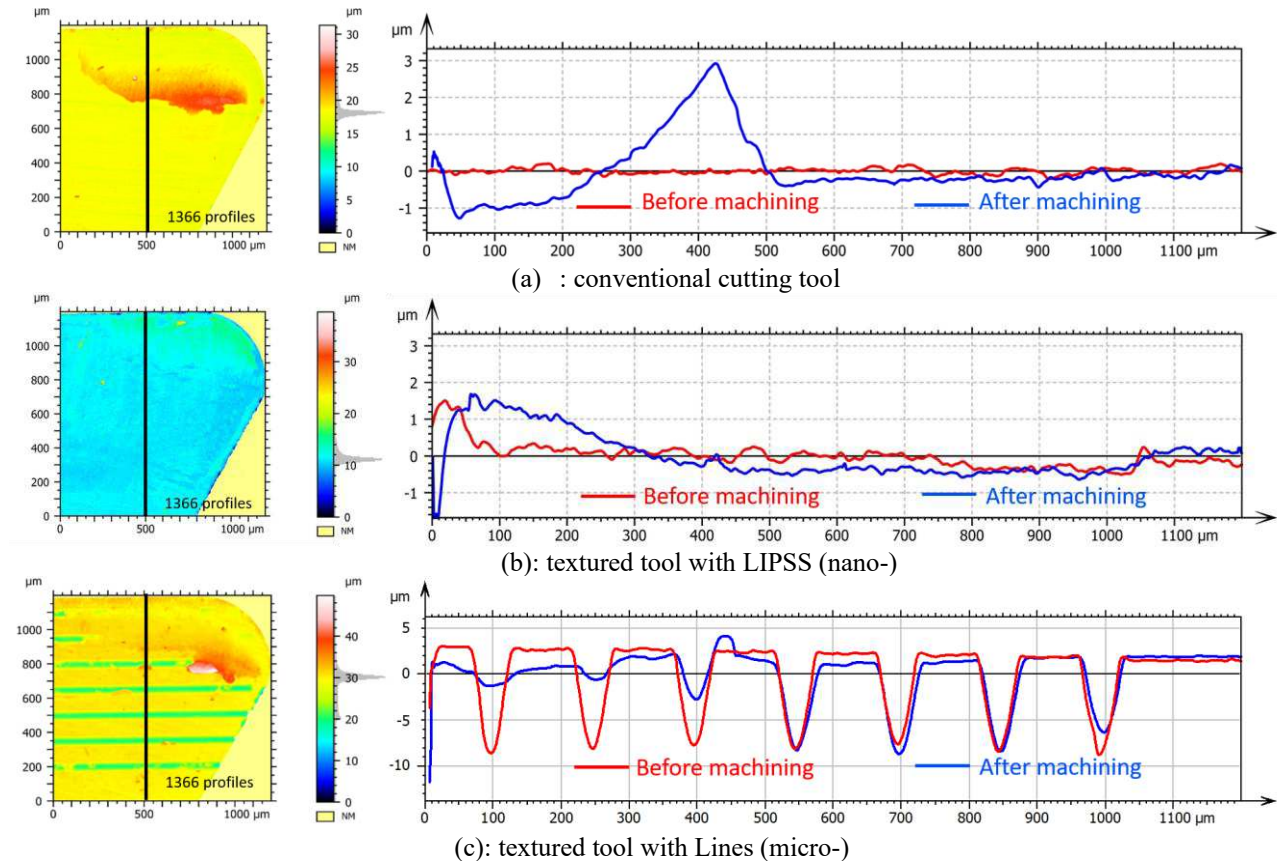


Fig. 10 SEM images of rake faces after machining for textured and non-textured tools



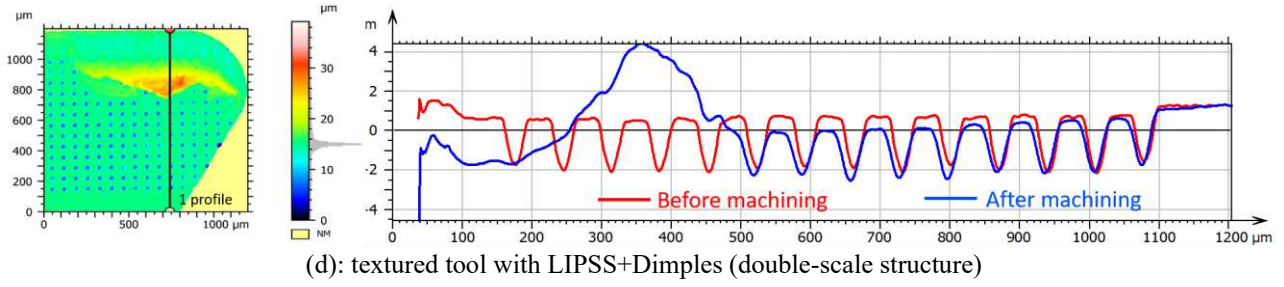


Fig. 11 2D average profiles of worn rake faces for different cutting tools: a) Non textured, b) Nanometric grooves, c) Micrometric grooves, d) Double-scale structure

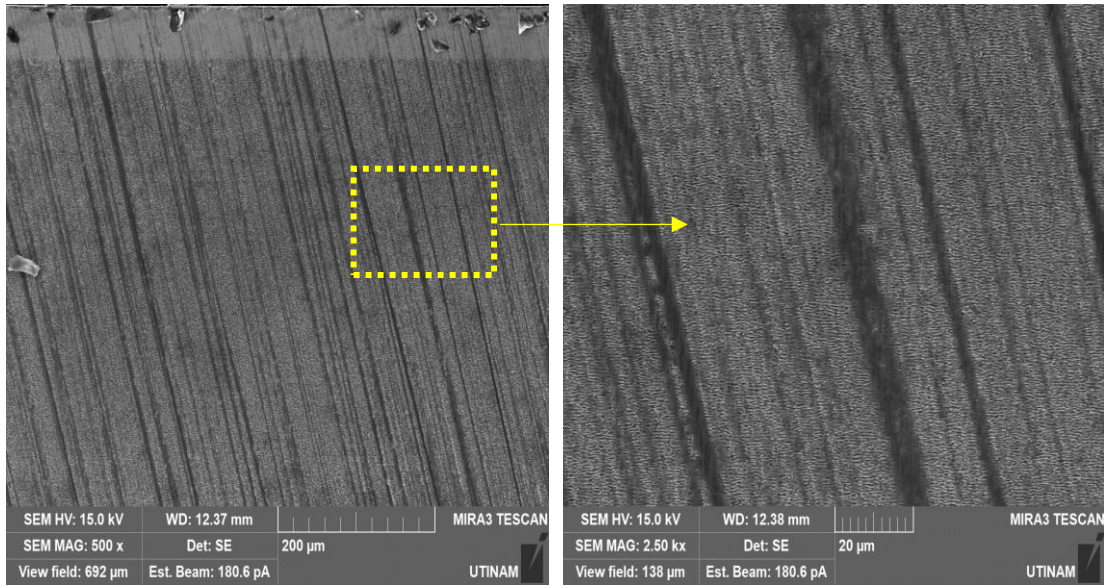


Fig. 12 SEM images of rake face of structured tool with LIPSS after turning aluminium

3.4 Chip analysis

At the end of cutting experiments, chip thickness was measured to estimate and compare shear angle and chip contact length for non-textured and textured tools. Six values of thickness were measured removing the starting and the ending part of chips. Equations presented below, based on Merchant's model, permitted to calculate shear angle and contact chip length values. In fact, Merchant described in his model the continuous chips formation in orthogonal cutting [20].

The chip compression ratio r_c can be defined in Eq. 1 as:

$$r_c = \frac{t_0}{t_1} = \frac{\text{Undeformed chip thickness (feedrate)}}{\text{Deformed chip thickness}} \quad (1)$$

The shear angle Φ , predicted by the Merchant's model, can be expressed in Eq. 2 as and represented in Fig. 13 [20]:

$$\Phi = \arctan\left(\frac{r_c \cos(\gamma)}{1 - r_c \sin(\gamma)}\right) \quad (2)$$

where r_c is the chip compression ratio and γ the rake angle of the tool.

The friction angle β is given by Eq. 3:

$$\beta = r_c + \arctan\left(\frac{F_f}{F_c}\right) \quad (3)$$

where r_c is the chip compression ratio, F_f the feed force and F_c the cutting force.

The chip contact length is calculated using expression in Eq. 4:

$$l_c = \frac{t_0 \sin(\Phi + \beta - \gamma)}{\sin(\Phi) \cos(\Phi)} \quad (4)$$

where t_0 is the undeformed chip thickness, Φ the shear angle, β the friction angle and γ the rake angle of the tool.

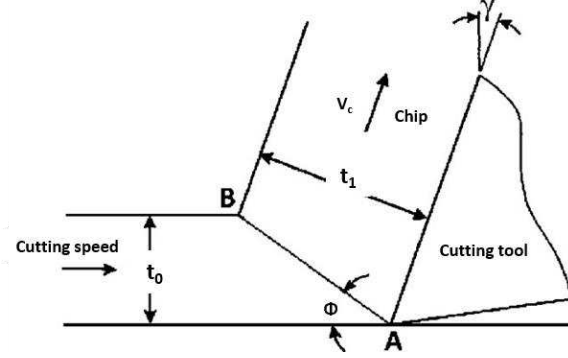


Fig. 13 Shear angle Φ , undeformed chip thickness t_0 , deformed chip thickness t_1 in orthogonal cutting [20]

Fig. 14 presents chip compression ratio and shear angle for each tested tool. An average ratio r_c (Eq. 1) is represented from six measurements of chip thickness. The tool textured with micrometric grooves produces a larger shear angle with an increase of 8.1% in comparison with the conventional cutting tool. This can be because micrometric grooves are much longer than cut width, which could be helpful for the cutting fluid to come into the tool chip interference.

Regarding tools textured with nanometric grooves and double scale structure, they produce a lower shear angle compared with the reference with a decrease of 4.4% and 40.3% respectively. For this experimental configuration, it is difficult to affirm the ability of cutting fluid to come into tool chip interference because employed cooling system consists of spraying lubricant in the contact between work material and tool and the coolant speed is less than chip rolling speed. Moreover, cutting speed affects the ability of the cutting fluid to come directly into tool chip interference.

Fig. 15 presents the chip contact lengths vs F_f/F_c ratios for initial cutting tool and textured ones. There is a linear evolution between chip contact length and F_f/F_c ratio. The tool textured with nanometric grooves (LIPSS) presents the highest macro friction coefficient and the greatest chip contact length.

A high F_f/F_c ratio for textured tool with LIPSS can be explained by the contact pressure at tool/chip interface which is important. The tool textured with LIPSS+Dimples shows a lower F_f/F_c ratio and l_c than tool textured with LIPSS. Dimples trap lubricant except the first ones near to cutting edge which are in a higher-pressure zone and are buried by aluminium. Concerning chip contact length and F_f/F_c ratio, the relative gap between tool textured with LIPSS and tool textured with LIPSS+Dimples is the added value of dimples which trap lubricant.

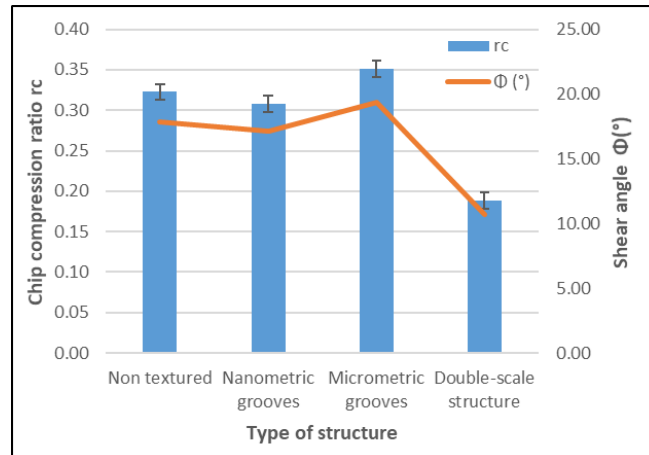


Fig. 14 Chip compression ratio vs shear angle for non-textured and textured tools

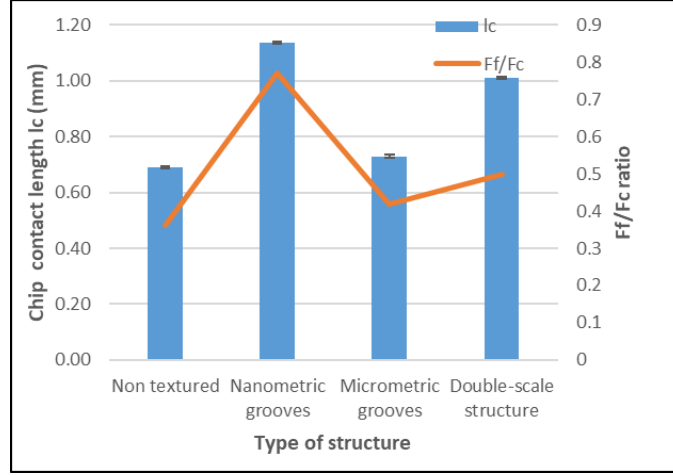


Fig. 15 Chip contact length vs F_f/F_c for non-textured and textured tools

3.5 Contact simulation results

The calculations led to very different mappings of the tool-chip contact with a variable distribution of stress on each surface. The indent had different contact geometries depending on texture and pressure, especially concerning the actual contact area, as shown in Fig. 16 and 17.

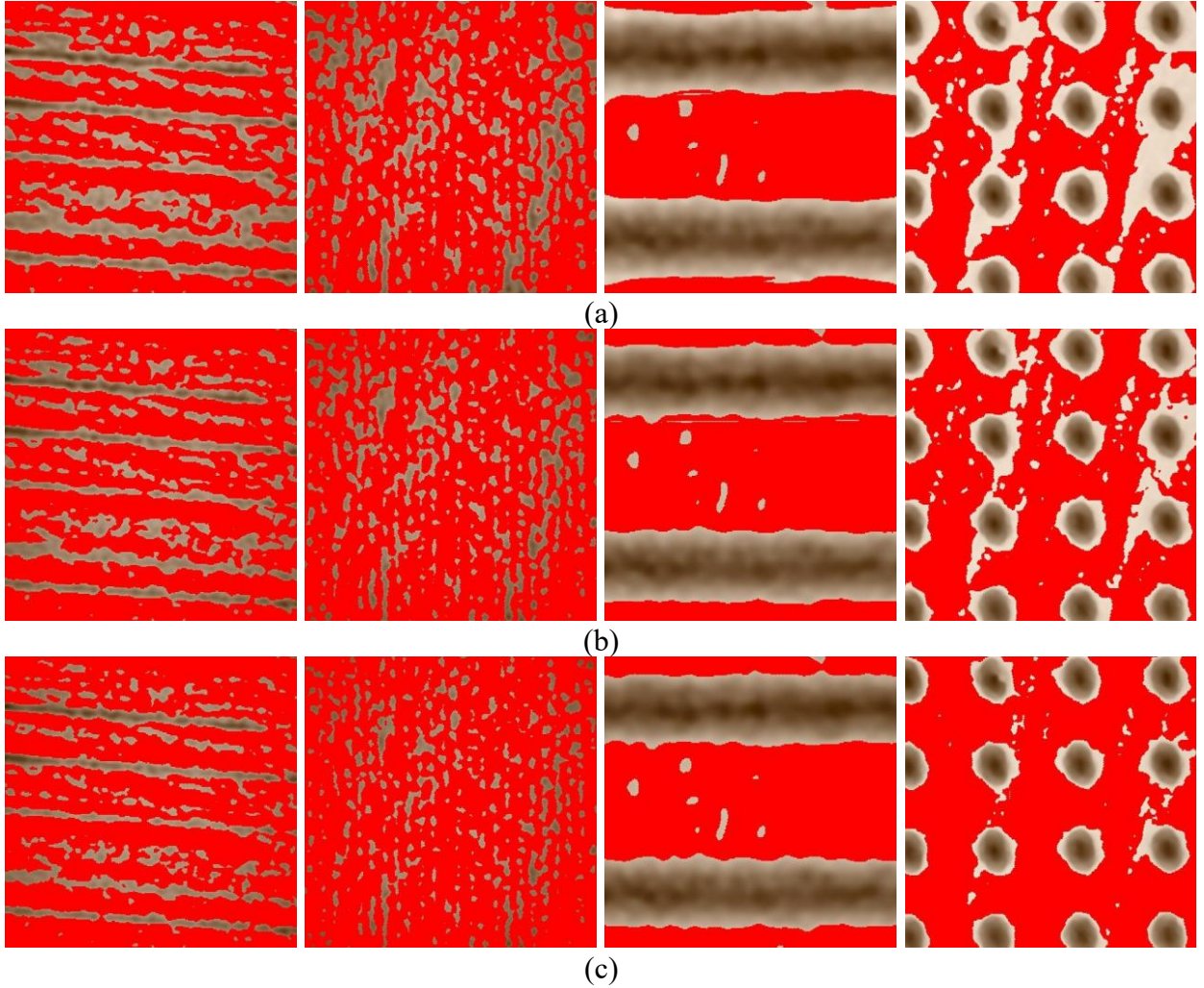


Fig. 16 Calculated chip actual contact area (S_{real}) on 0.24mm x 0.24 mm topographies, respectively for non-textured, nanometric lines, micrometric lines and double scale at $P_{app} =$ (a) 250 MPa, (b) 500 MPa, (c) 1000 MPa.

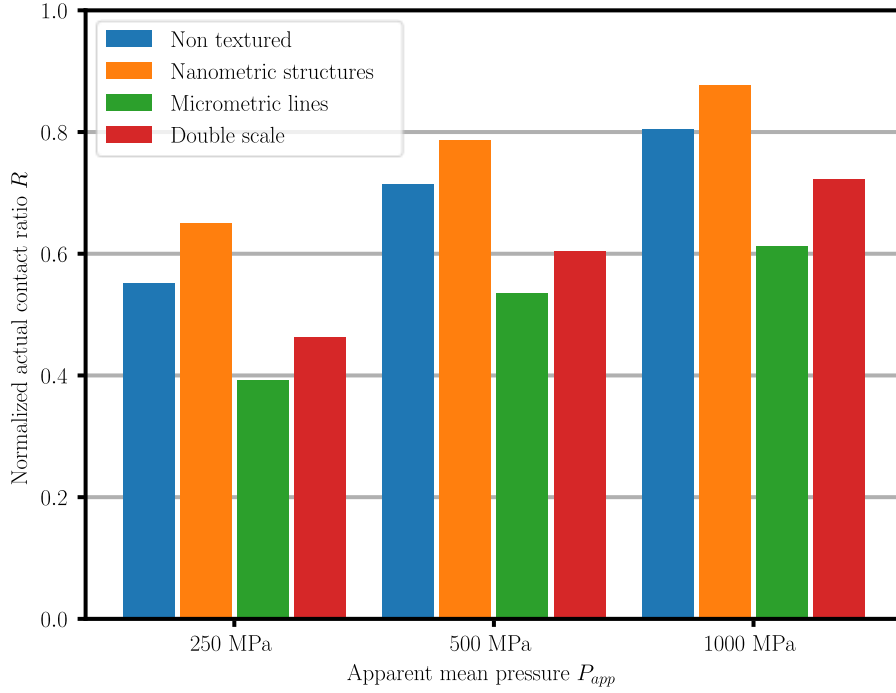


Fig. 17 Calculated contact area ratio R for different mean apparent pressures and textures

The most noticeable correlation is that the texture with the lowest R ratio leads to the greatest wear rate ($V_{b,rate}$) and the lowest rake face contact area (S_c). In this study, this corresponds to the micrometric lines. The same correlation appears for the nanometric structures (LIPSS), where an increase in the R ratio is associated with a reduction in $V_{b,rate}$ and an increase in S_c .

It can also be seen that some textures, especially nanometric and double scale, may allow micro-channels for the third body to evacuate wear debris out of the critical contact zone. Fig. 18 shows a 3D view of the vertical gap mapping between the two surfaces as explained in Fig. 5. The initial roughness has a non-neglectable impact on the tribological behaviour of the surface. In the following figure, the original tool is linearly grinded with the same orientation on the whole surface. The channels are the results of this first “texturing”.

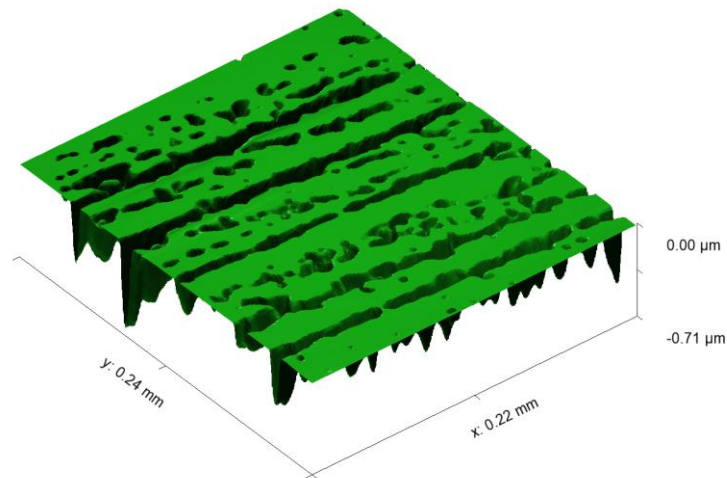


Fig. 18 Isometric view of under-load distance between the surfaces described in Fig. 5 for the non-textured tool with originally grinded channels.

4 Conclusions

This paper demonstrates the influence of carbide textured tools on the cutting performance of machining aluminium alloy in wet condition. Three sorts of structures have been tested: nanometric structure (LIPSS), micrometric structure (Lines) and double-scale structure (LIPSS+Dimples). We investigated the effect of this type of structure for aluminium turning with very basic cutting tool geometry and with no coating to underline the capacity of these textures to enhance cutting drastically and perhaps replace some more classical enhancements. The numerical simulation showed convincing results. The pressure-truncation model may be a well-fitting and quick approach to machining, where thermal softening and high-speed strain result in more complex calculations. Moreover, for the first time, a double scale structured tool combining nanometric and micrometric scales is tested for machining.

By changing type of structures on rake face of the tool, different responses are obtained regarding machining performance with the following findings:

- No significant difference between generated cutting force with textured and non-textured tools has been observed. Only, double-scale structured tool presented a lower cutting force reduced by 6.9% in comparison with conventional cutting tool. Feed force values of textured tools are greater than non-textured tool due to a higher contact pressure at tool/chip interface.
- Flank wear width is reduced by 91.5% and 79.7% with LIPSS and double-scale structure respectively. This result represents a major finding because it shows that rake face structuring had an influence on controlling flank face wear. These results were pointed out only once by Zhang et al. for stainless steel cutting [14] and correlates well with the simulation results.
- Rake face analysis after machining shows a lower height of adhesion on the tool with LIPSS compared to other tested tools. However, it induces an important macro friction coefficient at tool/chip interface since contact pressure is high.
- Chip analysis demonstrated an increase of shear angle value by 8.1% with tool textured with micrometric structure (Lines). It also highlighted a linear dependence between chip contact length and F_f/F_c ratio.
- At constant pressure, the numerical model gave a different actual contact area for each texture, which can explain some of the effects observed on the rake face like the increase of the rake face contact area. This then leads to a reduction of adhesion.
- The initial roughness caused by grinding also led to variable tribological behaviour concerning the third body and sliding regime. The simulation highlighted this possibility by showing that even under high load (1 GPa), the channels remain probably impactful.

To sum up, depending on which criteria of machining performance we are considering, conclusions that can be made are different. For small parts machining in swiss turning, where low cutting forces are required, textured tools presented in this study do not show any advantage. Most of the results in this study depend on the initial roughness and especially its orientation which can lower the individual effects of texturing. Nevertheless, even with different initial roughness, if the purpose is improving productivity and surface quality, tools textured with LIPSS or LIPSS+Dimples are much more beneficial when machining aluminium. Finally, if the aim is adhesion mitigation on rake face, tool textured with LIPSS is the best choice. The obtained results also indicate that the performed femto-second laser textures could also replace the use of a titanium-based coating on the cutting tool and then avoid reducing edge sharpness by increasing tool edge radius. This new approach could allow better finish on workpieces made of ductile materials and decrease the production costs by increasing tool life but also potentially decrease the tools price. By creating ripples on tool rake face, we estimated with our industrial partners that about 70-80 € could be saved on production costs by cutting edge, by limiting tool exchanges and increasing autonomous machining at night. Moreover, a femto-laser texturing operation on a cutting insert would be 2 or 3 times less expensive than a titanium-based coating. The environmental impact of tool post-processing should be lower too, compared to coating techniques.

The perspectives offered by this work are numerous. Scientifically, it is important to investigate the influence of the effect of textures on chip flow and wear on rake and flank faces. For example, how a simple texture on rake face change so drastically the wear on the clearance face on the tool? For the case of large grooves or dimples, this can be done at a mesoscopic scale by numerical simulation by changing the tool geometry considering textures [22], but also wear if needed. To investigate the contact at a lower scale, nano-tribological tests can be efficient [23], specifically to study the evolution of contact area, contact pressure and sliding speed on these textures, and the role of lubrication and its ability to reach the tool/chip interface. Moreover, the grinded texture effect must be isolated to fully understand the tool-chip interface role in flank wear. Industrially, another perspective is to enlarge obtained results by considering more complex coated tool with 3D geometry and potential presence of chip-breaker. Finally, it is now important to evaluate the environmental impact of such modifications in production of cutting tools and in their use and potential recycling. This criterion cannot be neglected anymore when optimizing manufacturing processes.

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Statements and Declarations

Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article. With the agreement of involved industrial partners, the presented results are free of commercial rights.

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