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Tool Geometry Optimisation for LCO_2 Assisted Milling of Ti6Al4V

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Abstract

Titanium alloy Ti6Al4V is of great importance to the aeronautical and medical sectors due to its mechanical properties such as a high strength-to-weight ratio and corrosion resistance. On the downside, machining Ti6Al4V can lead to accelerated tool wear and poor surface finish of the machined part due to its low heat dissipation capacity. Traditionally, oil and water based metalworking fluids (MWFs) have been used to overcome such issues. However, new regulations and eco-friendly manufacturing trends suggest that conventional MWFs should be minimised, as they are hazardous to the environment and workers' health. Additionally, titanium prostheses contaminated with oil can cause severe integration problems on the patient. This article researches the feasibility of replacing conventional emulsions with sustainable liquid carbon dioxide (LCO_2) cooling. For this purpose, an optimisation of the tool geometry (helix angle, clearance angle and cutting edge geometry) for LCO_2 assisted milling of Ti6Al4V was carried out, taking into account parameters such as cutting forces, surface roughness and the microstructure of the machined surface. This research contributes to the development of environmentally friendly and work safe manufacturing processes that meet the challenges of machining Ti6Al4V for aerospace and medical applications.

Keywords: Sustainable machining; LCO_2 cooling; Tool geometry optimisation; Ti6Al4V

1. Introduction

Titanium alloys such as Ti6Al4V are widely used in medical and aerospace industries due to their mechanical properties The high corrosion resistance and high biocompatibility of the titanium, make it a reliable choice in medical industry to manufacture orthopaedic and dental implants [1]. Moreover, as Ti6Al4V has a high strength-to-weight ratio, and good compatibility with other low-weight structural materials such as composites, it is a key material to develop lightweight aircraft structures and reduce fuel consumption during take-off [2]. This reduction in aircraft emissions has been in an upward trend promoted by the restrictions in NO_x and CO_2 emissions set by the Advisory Council of Aeronautical Research in Europe [3]. Aircraft components made of Ti6Al4V include structural components such as the cockpit window frame and fasteners, or the blisks in the fore turbofan engine [4].

However, Ti6Al4V is considered a material with poor machinability which creates rapid tool wear and surface integrity problems. This is due to the low thermal conductivity of the material, that prevents the heat dissipation through the generated chips and leads to high cutting temperatures at the tool (around 600 °C at the cutting edge, for V_c = 95 m/min [5]). This high temperatures promote diffusion and adhesion wear [6]. Water and/or oil based emulsions are usually employed as metalworking fluid (MWF) when cutting titanium, to avoid such machinability and surface integrity problems. However, these MWFs present hazards to the environment [7], and create dermal and respiratory conditions on the workers [8]. Additionally, for the industry of titanium prosthetics,

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machining the implants with oil-based MWFs can lead to integration problems in the patient [9]. For this reason, cooling alternatives with lower environmental and health impact, that reduce or eliminate emulsions are under research.

The use of sub-zero liquefied gases such as liquid nitrogen (LN_2) or liquid carbon dioxide (LCO_2) has proven to cool down the cutting zone without using oils, and thus avoiding oil contamination of the part, and pollution at the workplace.

Related to titanium alloys, some researchers compared the effects of these coolants in the cutting forces, temperatures, wear and tool life when milling Ti6Al4V alloy [10]–[12]. They found that cooling with LN_2 led to lower cutting temperatures, forces and stresses among the considered alternatives. The reduction of the cutting forces was 30% compared with minimum quantity lubrication (MQL). It was observed that combining MQL lubrication with LN_2 cryogenic cooling improved tool life by 32% compared to flood lubrication. In comparison with emulsions, tool life increased threefold, and surface roughness decreased by 40%.

On the downside, the use of LN_2 for machining operations is limited, due to the low temperature of the liquefied gas at room conditions (-197 ºC). Consequently, the handling, through the tool delivery, and combination with lubricant media becomes complicated. Liquid carbon dioxide (LCO_2) on the other hand, gives rise to the possibility of through the tool delivery or combination with MQL oils, as it can be stored at room temperature when pressurized at 57 bars.

Tapoglou et al. [13] showed that delivering supercritical CO_2 ($scCO_2$) through the tool resulted in a slight improvement in the surface roughness, in comparison to emulsion flood cooling when face milling Ti6Al4V. Rapid tool wear was observed when employing only $scCO_2$, however, this was greatly improved when combining $scCO_2$ cooling with MQL.

Sadik et al. [14] achieved a 300% improvement in tool life when using through the tool CO_2 compared to emulsion flood cooling. They determined that the most relevant wear type was notch wear, irrespective of the cooling condition. They also stated that CO_2 cooling reduces the risk of thermal cracking of the tools, delaying the chipping of the cutting edge. Through the tool LCO_2 cooling also presented promising results regarding tool life in other materials such as Inconel 718 and Gamma TiAl [15].

The literature has shown the potential of LCO_2 cooling for Ti6Al4V milling. However, the authors believe that the performance of this cooling technique could be further enhanced by creating designated tools for LCO_2 cooling, since sub-zero cooling affects the machining process differently from the more widely known emulsion cooling. Shokrani et al. [16] analysed the effect of different tool geometries under LN_2 cooling, and concluded an optimised tool for LN_2 assisted milling of Ti6Al4V. Nevertheless, to the best of authors knowledge, very little progress has been made regarding tool geometry optimisation combined with cooling conditions, specifically for LCO_2 assisted milling of Ti6Al4V.

Therefore, in this study, a sensitivity analysis of varying different end mill geometrical parameters under conventional emulsion cooling and LCO_2 cooling was carried out. As a result, an optimised tool design for LCO_2 assisted milling of Ti6Al4V was obtained.

2. Experimental procedure

Eight different tool geometries were tested under emulsion and LCO_2 cooling environments for Ti6Al4V side milling experiments. The cutting forces, surface roughness and microstructural damage in the workpiece were evaluated to find the optimal tool geometry and MWF combination.

2.1. Experimental setup

A LAGUN GVC-HS 1000 machining centre was employed to carry out the milling experiments. Ti6Al4V plates measuring 40x40x5 cm^3 were clamped in a fixture that was bolted to a Kistler 9272 dynamometer for force monitoring (Fig. 1a). The free side of the plates (40 mm) was machined, and the cantilever of the workpiece was kept constant by adding calibrated blocks after each pass.

The coolant was delivered through the tool, using a specifically designed tool holder for the testing conditions were LCO_2 cooling was applied (Fig. 1a). The LCO_2 flow rate was controlled with a needle valve, and the pressure was monitored with a manometer to ensure the liquid phase (Fig. 1b). The specifically designed tool holder allows through the tool delivery of LCO_2 without needing to retrofit the spindle of the machine tool. On the downside, the creation of carbonic snow due to LCO_2 expansion could block the conducts inside the tool holder when using flow rates smaller than 0.5 kg/min for an extended machining period. Also, preliminary experiments showed that the bearings and washers inside the rotary unit of the tool holder limit the rotation speed to 3000 rpm.

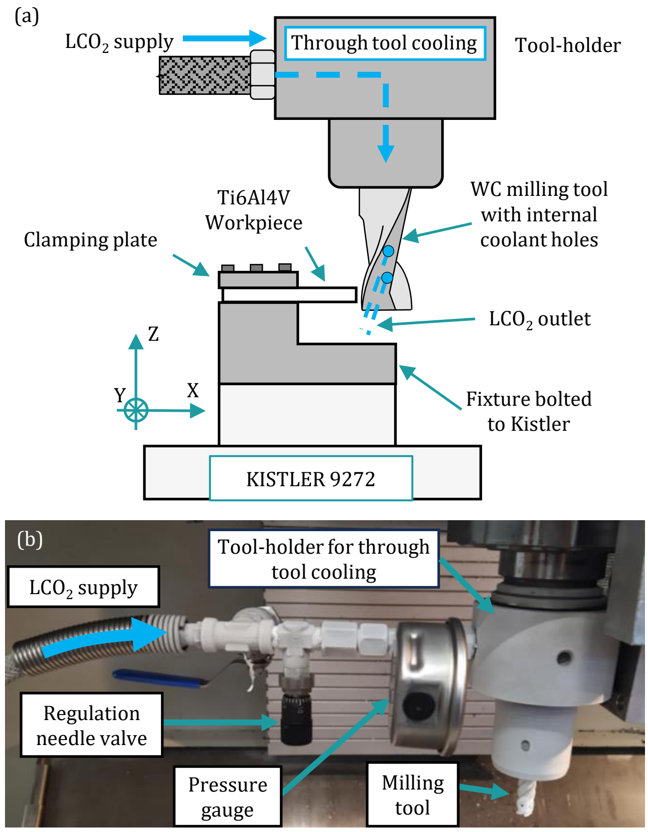


Fig. 1: (a) Schematic view of the experimental setup; (b) Through the tool LCO_2 flow rate control with a regulating needle valve.

The cutting forces recorded with the Kistler 9272 were filtered using a low-pass filter at 150 Hz, which was the lowest damped frequency of the set-up shown in Fig. 1. To evaluate the surface integrity, the surface roughness parameters that define fatigue strength (R_a, R_t, and R_z) were measured, following the study by Arola et al. [17]. A Mitutoyo Surftest SJ210 Rugosimeter with a probe of 2 µm was employed. Three measurements of 3 mm were performed at the beginning, middle and end sections of the machined sample (Fig. 2b), completing a measured length of 9 mm. The measuring direction was opposite to the feed, and a filter of λ = 0.8 mm was applied. Defects in the microstructure were observed using a Leica DM i8C optical microscope with a × 50 magnification. 15 mm specimens were polished and etched, and the upper surface normal to the axis of the tool was observed.

2.2. Experimental plan

As the experimental plan of Fig. 2a shows, a 2^4 Design of Experiment (DOE) was designed by varying the cooling/lubrication from emulsion to LCO_2, and three different tool geometry parameters. These were the helix angle (ε), clearance angle (α) and cutting edge radius (r_c). The three main cutting force components, as well as the surface roughness and microstructural damage were evaluated for each tested condition (Fig. 2b). In Table 1 the values of the variable input parameters employed in this study are listed.

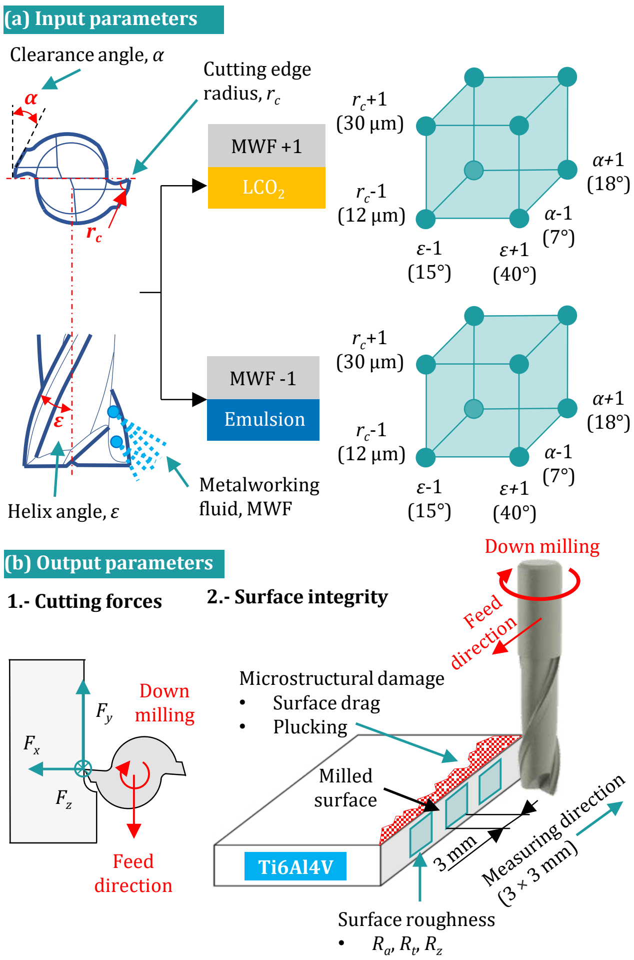


Fig. 2: (a) Variable input parameters tested in the experimental campaign; (b) Cutting force and surface integrity parameters monitored for each test.

Table 1: Values of the variable input parameters tested in the DOE.

Input parameter	Lower value (-1)	Upper value (+1)
Cutting edge radius (r_c)	12 µm	30 µm
Helix angle (ε)	15°	40°
Clearance angle (α)	7°	18°
Metalworking fluid (MWF)	Emulsion	LCO_2

Cutting parameters for finish machining were selected, as these operations are the ones which determine the final surface integrity of the components. These parameters were set constant at V_c = 80 m/min, f_z = 0.16 mm/rev, a_p = 5 mm and a_e = 0.2 mm, following the recommendations of the toolmakers [18], [19]. The limitations in rotational speed set by the tool holder employed for LCO_2 (maximum 3000 rpm), were also taken into consideration. The diameter of all the milling tools employed was 10 mm.
The LCO_2 coolant flow rate was kept constant at 0.5 kg/min, by controlling it with a regulating needle valve, and the pressure of the through the tool emulsion cutting was set at 10 bar. Every experimental condition was repeated three times to determine the uncertainty.

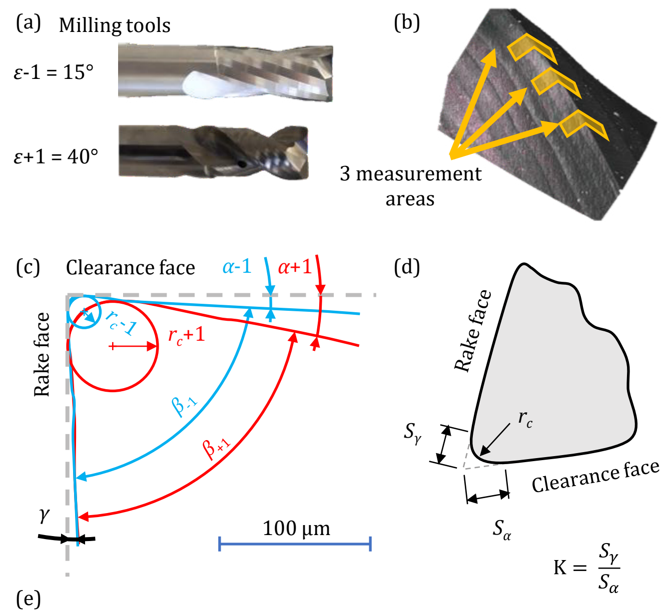
2.3. Materials and tools

The workpiece material was aeronautical grade alpha-beta Ti6Al4V alloy, with the mechanical properties shown in Table 2. Uncoated carbide (WC) tools were employed in all experiments. End mills with different helix angles (ε), namely 15° and 40° (Fig. 3a), underwent clearance angle (α) and cutting edge radius (r_c) modifications to achieve all the geometrical parameter combinations specified in Table 1.
The tools were initially fabricated with the lower values (-1) of α and r_c, (7° and 12 µm subsequently). After completing the experiments with this geometrical parameter combination, a set of milling tools were ground to modify r_c until meeting the specified upper value (+1) of 30 µm, while the clearance angle was kept at the (-1) value. Another set of tools were ground to modify the α from 7° to 18°, while keeping the cutting edge radius at the lower value. Once the experiments with those tool geometries were completed, the tools were ground again to achieve the upper values in both r_c and α.

All the tools (as-received and modified) were checked using an Alicona IF IG4 with a × 5 magnification. The lateral and vertical resolution were 3.6 µm and 410 nm, respectively, to properly discretise the cutting edge geometry. The ring light and polariser were used to minimise errors due to reflection. As it can be seen in Fig. 3b, three areas were characterised for every side cutting edge. To validate the modification of α, the variation of the wedge angle (β) was observed. Knowing that the rake angle (γ) is constant, a reduction in β indicates an increase in α. In Fig. 3c and e, the comparison of an as-received cutting edge profile (blue lines) and a modified one (red lines) is shown. To ensure that the regrinding process did not affect the force distribution along the cutting edge, the ratio of the rake face edge length ($S\gamma$) to the clearance face edge length ($S\alpha$) was calculated according to [20]. The calculation of this ratio (also known as the form factor or K-factor) is shown in Fig. 3d.

Table 2: Mechanical properties of Ti6Al4V alloy

Mechanical property	Value
Tensile strength [MPa]	Longitudinal: 921
	Transversal: 967
Tensile strength, ultimate [MPa]	Longitudinal: 973
	Transversal: 967
Elongation [%]	Longitudinal: 12.5
	Transversal: 15



(e)

Tool profile	Cutting edge radius, r_c [µm]	Form factor, K [-]	Wedge angle, β [°]	Clearance angle, α [°]
As-received (r_c-1; α-1)	11.9	1.08	83.2	6.8
Modified (r_c+1; α+1)	28.3	1.12	72.4	17.6

Fig. 3: (a) As-received tools; (b) Side cutting edge characterisation; (c) As-received and modified tool cutting edge profile comparison; (d) From factor calculation [20]; (e) As-received and modified tool geometrical parameters.

3. Results and discussion

3.1. Cutting forces

Fig. 4. shows the effect of increasing each input detailed on Table 1 from (-1) to (+1) values, on the cutting forces. As it can be observed the most critical tool geometrical parameter was the helix angle (ε), as it decreased the radial (F_x) and tangential (F_y) cutting force components, while increasing the axial one (F_z). The cutting forces, specially F_x were reduced when milling with greater clearance angles (α). Similar tendencies were observed by Ma et al. when milling Inconel 718 [21]. As they explained, the clearance angle determines the contact area between the flank face and the machining surface. Therefore, a greater clearance angle results in smaller contact area, and thus, reduced frictional forces. Increasing the cutting edge radius (r_c) also increased F_x, showing that greater radial cutting forces are obtained as the tool wears down.

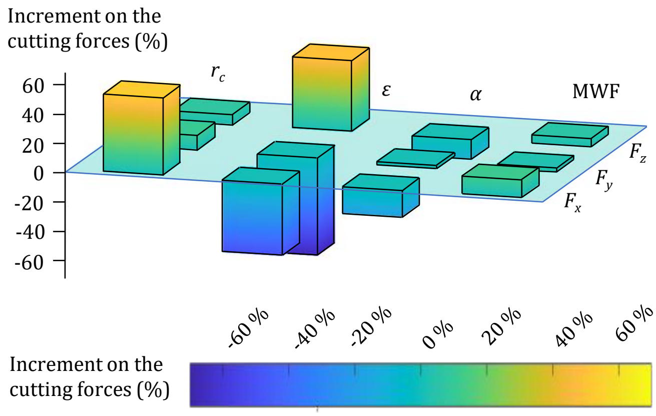


Fig. 4: Effect of increasing the variable inputs of the DOE from the (-1) to the (+1) values on the three components of cutting forces.

Using through the tool LCO_2 cooling (MWF+1) instead of emulsion cooling (MWF-1), generated an increase in the forces. This could be by a combination between the increase in the coefficient of friction generated by the LCO_2 snow [22], and the increase in material flow stress due to the cold temperatures [23].

3.2. Surface roughness

The average values and standard deviation of the three surface roughness measurements are shown in Fig. 5. Similar to the cutting forces, varying the helix angle had the greatest effect on surface roughness. An increase in ε improved the surface finish, this could be due to a reduction in F_x and F_y promoted by the increase in helix angle.

Increasing α from 7° to 18°, helped to slightly reduce the surface roughness. This was especially noticeable when machining under emulsion cooling. Milling with greater cutting edge radius resulted in a worse surface finish for all tested conditions. This was expected, since tools with greater radii create greater feed marks than sharp tools [24].

Regarding the effect of the MWF employed, a worse surface finish was observed overall when milling with LCO_2 cooling. This might be because, as opposed to emulsion cooling, LCO_2 does not provide any lubrication to the cutting zone and the coefficient of friction increases. Pušavec et al. [22] proved by carrying frictional tests, that the coefficient of friction when using pure LCO_2 cooling without any lubrication can be almost double compared to emulsion cooling. Gutzeit et al. [25], compared the surface quality obtained when side milling Ti6Al4V with sub-zero emulsion (-23.5 °C) and LCO_2 cooling. They also observed that the lack of lubrication in LCO_2 cooling brings adverse results in surface roughness.

3.3. Microstructural analysis

As the cutting forces results in Fig. 4 and the surface roughness results in Fig. 5 have shown, the tool geometrical parameters with the greatest influence were the helix angle (ε), followed by the clearance angle (α). Hence, the analysis was focused on observing the microstructural alterations generated by these geometrical parameters under different MWFs. All analysed samples were machined using tools with r_c = 30 µm.

Samples of 15 mm length were analysed (Fig. 6a), and examples of the obtained microstructures are shown in Fig. 6b. The most relevant damage form in all samples was surface drag; however, no significant damage was observed despite of varying the tool geometry or coolant (Fig. 6c). This could be due to using machining parameters for finishing operations, which generated very little surface drag on the microstructure. Similar results were observed by Milton et al. [26], who reported little to no plastic deformation after finish machining Ti6Al4V. Additionally, the experiments carried out by [27] under similar conditions (α = 7°; f_z = 0.12 mm/rev), showed that the machining process has little effect on the Ti6Al4V microstructure, for speeds under V_c = 100 m/min.

Therefore, it was concluded that finish machining does not create critical microstructural damage on Ti6Al4V, regardless of the tool geometry or coolant. The authors are aware however, about the influence parameters like cutting-edge radius or coolant on the residual stresses [28], which will be considered for future works.

4. Conclusions

In this work a sensitivity analysis of varying specific tool geometrical parameters under emulsion and LCO_2 cooling has been carried out. The main conclusions are the following:

- To achieve improved surface finish when side milling Ti6Al4V high helix angles (ε) and clearance angles (α) should be employed, being ε the most influential parameter. A high ε decreases the radial (F_x) and tangential (F_y) cutting force components, at expense of increasing the axial one (F_z), and high α reduces the friction between the tool and the workpiece.
- Tool geometry had a greater effect on cutting forces and surface finish than the MWF. This could be due to employing small a_e values. As the engagement of the tool was less than 5% of the tool diameter, the chip evacuation and cutting temperature were not problematic, making the influence of the coolant less relevant.
- The lubrication provided by the emulsion cooling helped to achieve a better surface finish, compared to LCO_2 cooling.
- No critical microstructural damage was observed for any of the tested conditions. This might be due to using finish machining parameters, which created minimal plastic deformation of the microstructure. Evaluation of the residual stresses will be considered for future works.

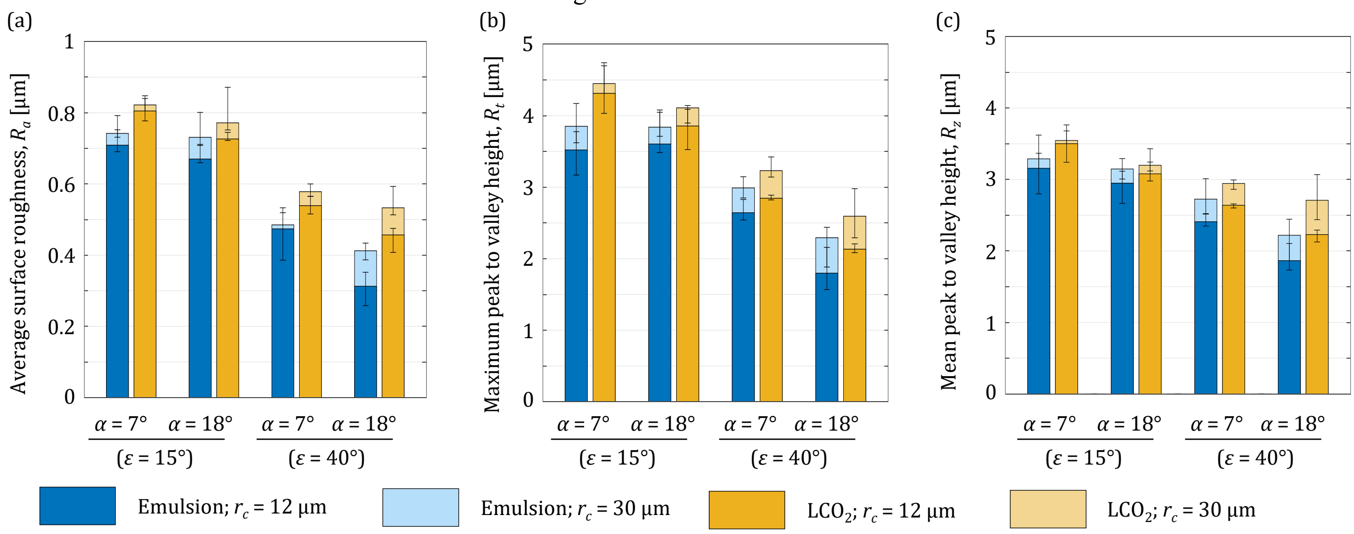


Fig. 5: Surface roughness parameters measured when varying tool geometrical parameters and metalworking fluid: (a) R_a; (b) R_t; (c) R_z.

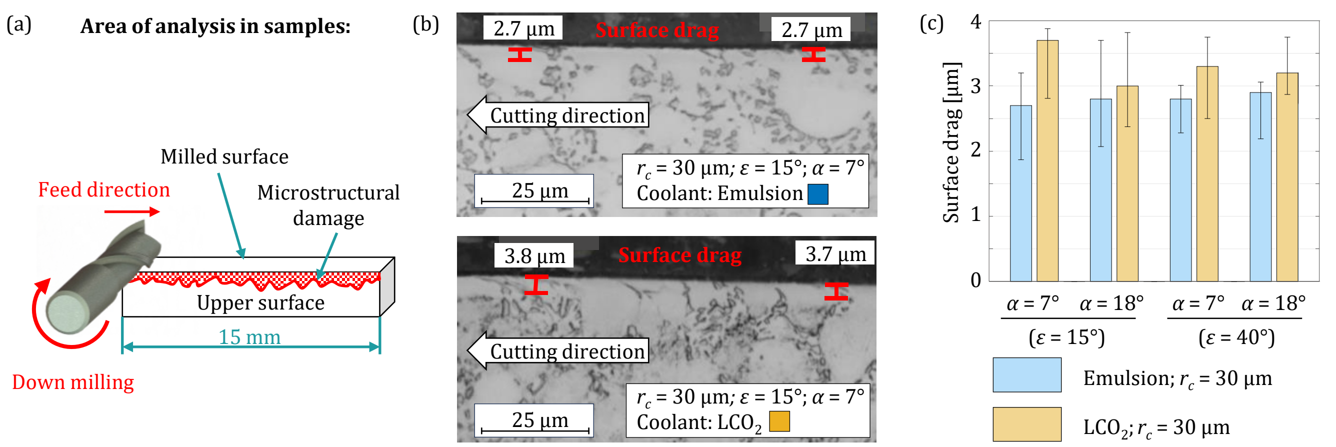


Fig. 6: (a) Description of analysed area; (b) Microstructures of machined samples; (c) Surface drag when varying tool geometry and metalworking fluid.

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