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The influence of single-channel liquid CO_2 and MQL delivery on surface integrity in machining of Inconel 718

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Abstract

Sustainable machining of difficult-to-cut materials requires effective cooling and lubrication techniques. To substitute conventional flood cooling and lubrication, different techniques such as cryogenic cooling and/or minimum quantity lubrication (MQL) can be used. Liquid carbon dioxide (LCO_2) can be pre-mixed with different lubricants before its delivery to the cutting zone. This article investigates the influence of this recently developed cooling and lubrication method on surface integrity characteristics in milling of Inconel 718. Surface roughness, surface topography and microstructure were evaluated for flood lubrication, dry cutting and LCO_2 machining using a single-channel LCO_2 and MQL strategy. Moreover, two different lubricants were evaluated for MQL: (i) conventional MQL oil and (ii) solid lubricant molybdenum di-sulphide (MoS_2). In addition to being environmentally friendly, MoS_2 lubricated LCO_2 showed comparable surface characteristics to flood lubrication. Also, the use of lubricated LCO_2 resulted in higher part surface cleanliness compared to flood lubrication.

Keywords: Liquid carbon dioxide; MQL; Inconel 718; surface integrity

1. Introduction

Inconel 718 is a nickel-based super alloy widely used at high-temperature environments due to its excellent high temperature strength and corrosion resistance. Common applications of this alloy include hot sections of gas turbines in aerospace industry, chemical and steam power plants, etc. In such environments, operating conditions require high resistance to mechanical and thermal loads. In addition, high safety requirements put main focus on reliability and fatigue life. It is well known that surface integrity is of great importance as most of the fatigue related failures originate either at the surface or near the surface. Hence, the research of surface integrity in machining is of high importance [1,2].

Inconel 718 is categorized as difficult-to-cut material. The reason for poor machinability of this alloy is due to its superior mechanical and thermal properties such as low thermal conductivity. Poor machinability of this material causes many detrimental effects to the machined surface and subsurface such as generation of burrs, material smearing, heat affected layers, cracks and arising tensile residual stresses [3,4]. Therefore, to obtain a suitable surface integrity, a special care must be taken in selecting tool material and coating, tool geometry, machining strategies and parameters as well as cooling and lubrication techniques.

Today, metal working fluids (MWFs) are widely used as standard cooling media for machining heat-resistant materials like Inconel 718. But large volumes of MWFs' usage are problematic in terms of occupational health safety, maintenance, costs, recycling difficulties and machined part cleanliness [5,6]. Therefore, possible alternatives to MFWs such as dry, cryogenic and MQL machining are gaining interest both in the industry as well as in the scientific community. Cryogenic machining has been under rather intensive

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development in the last decade with the emphasis on liquid nitrogen – LN_2 [7]. However, due to its non-lubricating properties along with complicated delivery system its wider use in industrial sector is somewhat limited. In contrast, liquid carbon dioxide (LCO_2) in combination with MQL can provide both cooling and lubrication [8] and is more easy to deliver, e.g. through a machine-tool spindle. Although its cooling capabilities are lower compared to emulsion [9], LCO_2 leaves dry and clean surface after machining and still prevents the detrimental, thermally induced deterioration of the surface integrity and tool wear associated with high temperatures.

To reduce friction in the cutting zone, various liquid lubricants are used either as straight oils or water based (emulsified). Friction reduction lowers the generated heat thus improving both tool life and quality of the machined surface. Solid lubricants such as molybdenum disulfide (MoS_2) or graphite are most commonly used in extreme environments such as vacuum or at temperatures which exceed the operational range of oil-based lubricants. In machining, only a handful of studies which feature solid lubricants as additives have been conducted so far.

Researchers observed prolonged tool life, reduced surface roughness, cutting temperature and cutting forces when using MoS_2 as an additive to straight MQL oil [10-12]. The use of graphite as an additive to straight MQL oil also showed improved surface roughness and tool life in [13] and [14]. Other less known solid lubricants such as SiO_2 in [15] and [16], TiO_2 in [17], diamond nanoparticles in [18] and [19] and graphene in [20] also proved to be viable additives to MQL oils for improving surface roughness and tool life. Two studies [21] and [22] report improved surface roughness and tool life in turning of Inconel 718 when adding solid lubricants (MoS_2, WS_2 or graphite) into straight MQL oil, showing their potential in machining of difficult-to-cut materials. In the cases above, the solid lubricants are always suspended in oil and delivered to the cutting zone by means of conventional MQL. Potential benefits of machining with solid lubricants, suspended in cooling medium such as LCO_2 are therefore yet to be discovered.

The goal of this paper is to evaluate the performance of novel strategy based on solid lubricated LCO_2. MoS_2 is suspended in LCO_2 and delivered to the cutting process via MQL as LCO_2 + MQL (MoS_2). In this study, finishing milling of Inconel 718 is performed under five different cooling and lubrication techniques: (a) dry; (b) flood lubrication; (c) LCO_2; (d) LCO_2 + MQL (oil) and (e) LCO_2 + MQL (MoS_2). After milling, the cleanliness of the surface was evaluated based on determination of fluorescence intensity using a dedicated measuring device. Surface roughness was measured using optical 3D measurement system. Surface topography and microstructure were obtained using scanning electron microscopy. Lastly, the feasibility of solid lubricated LCO_2 as a replacement for conventional dry and flood lubrication techniques is discussed.

2. Experimental setup

2.1. Surface preparation

Ten round samples (d = 50 mm) of Inconel 718 (solution and precipitation treated) were side milled using TiAlN coated carbide end mill with the diameter of 6 mm. Climb milling machining strategy was used. The machining parameters for finishing were: a_p = 12 mm, a_e = 0.1 mm, f_z = 0.05 mm and v_c = 60 m/min. Two "cleaning" passes with the same parameters but a_e = 0.25 mm were performed prior to the final finishing pass. For the "cleaning" passes, TiAlN coated end mill with diameter of 20 mm was used. Two surfaces were generated on each sample. New end mills were used for milling each sample. Each cooling and lubricating technique was tested on two samples. Nozzle (d = 1 mm) for delivery of LCO_2 + MQL was oriented to the tool roughly in the middle of the a_p depth, with an angle of approx. 30° relative to the xy plane and an angle of approx. 15° relative to the yz plane. Nozzle for flood lubrication (d = 3 mm) was placed in same position. Both nozzles were positioned as closely to the tool as possible and delivered the cooling and lubrication media to the tool directly before it entered the workpiece. Fig. 1 shows a clamped sample after finishing pass and approximate position of the nozzle.

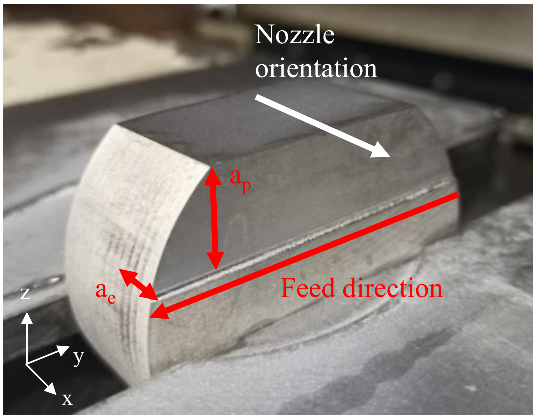

Fig. 1. Inconel 718 machining setup

The emulsion used for flood lubrication was Blaser Vasco 6000 with 7% concentration. When using LCO_2 + MQL strategy, the flow rate of the LCO_2 was kept constant at 200 g/min while the flow rate of the MQL (oil) was 120 ml/h and flow rate of the MQL (MoS_2) was 40 g/h. For MQL (oil) strategy a prototype MQL oil was used – specially designed for lubricating LCO_2. For more information, refer to Oil D in Table 1 in [8]. For MQL (MoS_2), solid lubricant MoS_2 with the average particle size of 5 µm was used.

2.2. Cleanliness measurements

Cleanliness of machined surfaces was measured using SITA CleanoSpector, which focuses and radiates UV light onto the surface and the contamination fluoresces. It is sensitive to most oils and MoS_2. The intensity of the fluorescence is proportional to the layer thickness of the contamination. This intensity is measured in RFU – Relative Fluorescence Unit (FluoLevel) and is displayed on a scale from 0 – 500. Diameter of measuring point is 1 mm. Each machined surface was measured three times (Fig. 2), resulting in 12 measurements for each cooling and lubrication condition. Prior to measurements, the surfaces were cleaned with a dried compressed air.

The cleanliness requirements are usually determined for each component separately based on its functionality or further processing operations. Therefore, the results reported in this study serve only as a method for comparing the (relative) surface cleanliness after machining with different cooling and lubrication techniques.

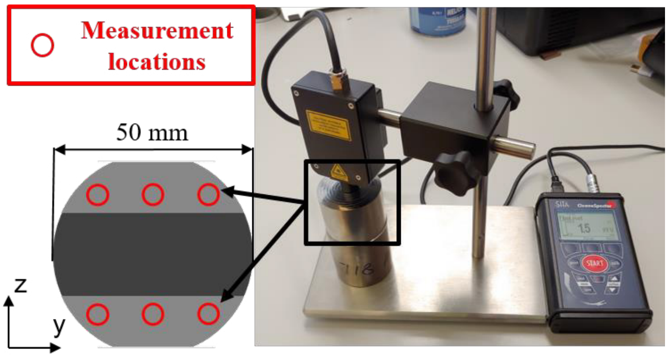

Fig. 2. Surface cleanliness inspection with SITA CleanoSpector

2.3. Surface roughness measurements

Surface roughness was measured using an optical 3D microscope (Alicona InfiniteFocus SL). Measurement area for each machined surface was 5 x 5 mm . The location of the measurement area on surface was always the same for every sample, positioned in the center of the machined surface. Roughness on each surface was measured in three directions as shown below: Fig. 3a parallel to the feed direction; Fig. 3b perpendicular to the feed direction and Fig. 3c perpendicular to the feed marks. Measured roughness parameters included average roughness R_a and maximum height of the profile R_y. For each cooling and lubrication technique, R_a and R_y were averaged based on 12 measurements.

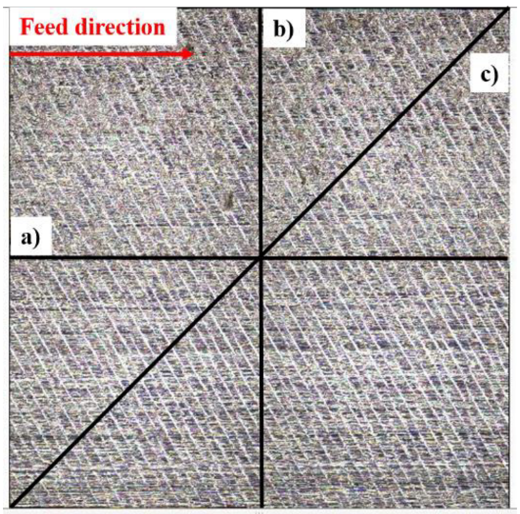

Fig. 3. Surface roughness measurement directions

2.4. Surface topography and microstructure

Topographical and microstructural images of face milled surfaces were examined using scanning electron microscope (SEM). The instrument used was LEO Gemini 1550 equipped with a field emission gun and the imaging was done at an acceleration voltage of 5Kv.

3. Results and discussion

3.1. Surface cleanliness

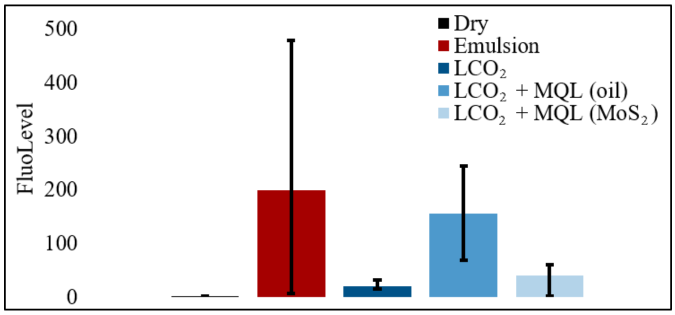

Fig. 4. Surface cleanliness of machined surfaces

Dry machining resulted in the lowest average FluoLevel value of 1 (Fig. 4). Average FluoLevel for wet machining was approx. 200. Emulsion stains can be problematic once the emulsion has dried out on the surface, leaving behind areas of high contamination. This non-uniformity of the cleanliness was observed on the surface of the workpiece, resulting in high variation between the measured FluoLevel values (Fig. 4). The use of unlubricated LCO_2 as a coolant resulted in average FluoLevel of 20 with low variation (Fig 4). This can be attributed to small amounts of contamination inside the supplying lines and LCO_2 itself. The addition of MQL (oil) increased cleanliness value to approx. 156 (Fig. 4). This is to be expected, as thin oil layer is deposited to the surface during the machining. This thin layer is only partially removed by using dried compressed air. MQL oil can be soluble in LCO_2 [8], thus CO_2 snow cleaning could be a viable option for cleaning the parts, machined with the assistance of LCO_2 + MQL (oil).

By replacing oil with MoS_2, lower average FluoLevel value of 38 was obtained (Fig. 4). It can be assumed that a small number of MoS_2 particles remained on the surface due to mechanical loads during machining. Other particles did not adhere strongly to the surface and were removed using compressed air. To remove the remainder of the MoS_2 particles, CO_2 snow cleaning could be used [28]. In conclusion, the use of LCO_2 + MQL (MoS_2) provided the cleanest cooling and lubrication technique where both cooling and lubrication requirements are satisfied.

3.2. Surface roughness

The surface roughness values of the machined surfaces with different cooling and lubrication techniques are presented in Fig. 5. Both parameters R_a and R_y followed similar trends. The lowest average roughness of 0.80 µm was obtained using LCO_2 + MQL (MoS_2), closely followed by flood lubrication which resulted in average roughness of 0.83 µm. Dry machining and unlubricated LCO_2 resulted in R_a of 0.94 and 1.02 µm, respectively. Interestingly, the use of LCO_2 + MQL (oil) resulted in highest average roughness of 1.09 µm. Maximum height R_y was the lowest with the use of flood lubrication at 6.9 µm, followed by LCO_2 + MQL (MoS_2) at 7.3 µm. Dry machining and unlubricated LCO_2 yielded 7.5 and 8.1 µm, while LCO_2 + MQL (oil) had highest peak-to-valley roughness of 9.3 µm.

When comparing dry and flood lubrication, opposing results can be observed in turning, where higher temperatures led to decreased roughness in [4]. In milling, however, higher temperatures in dry promoted higher adhesion and material smearing, resulting in poor surface quality.

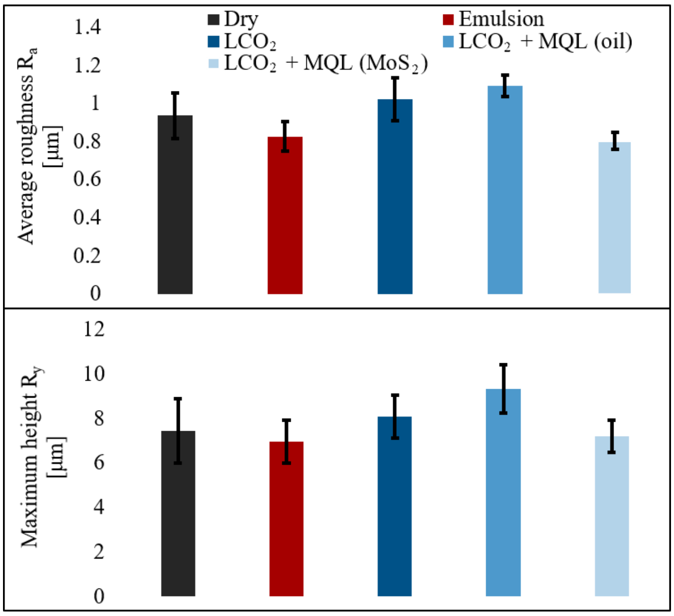

Fig. 5. Surface roughness of machined surfaces

This is also demonstrated when comparing dry and cryogenic (LN_2) milling of Inconel 718 in [23] and [24]. Considering the cooling aspect, the use of unlubricated LCO_2 did not help decrease the surface roughness. This could be attributed to external delivery of LCO_2. As the LCO_2 is depressurized, phase change occurs, and the heat is extracted from its surroundings. If the LCO_2 is delivered through the tool, this effect is much more pronounced as the phase change is already starting to occur inside the tool. Therefore, through tool delivery of LCO_2 should result in higher cooling effects compared to its external delivery and ultimately, lower surface roughness.

In finishing processes, lubrication plays an important role in surface quality. The poor performance of LCO_2 + MQL (oil) could be attributed to incompatibility of oil and workpiece material. The used oil is specifically designed to be mixed with LCO_2 and is therefore still in development phase. Conventional MQL can provide comparable surface roughness to flood lubrication [25]. Studies [26] and [27] report different influence of LN_2 + MQL on surface roughness, indicating the need for careful lubricant selection. By doing so, LCO_2 + MQL (oil) should be able to achieve better results than reported as this strategy results in smaller oil droplets compared to conventional MQL [8].

Dry and unlubricated LCO_2 performed similarly, while the addition of MoS_2 to LCO_2 vastly improved the surface roughness. This is in agreement with study [3], where researchers proposed the use of MoS_2 tool coatings when machining Inconel 718. Researchers in studies [21] and [22] also reported positive influence of solid lubricants on surface roughness when finish turning Inconel 718. Strong differences between different lubricants show the importance of their selection for such operations.

3.3. Surface topography and microstructure

Fig. 6 shows the topographies of the machined surfaces. Smearing of the material is visible on all surfaces. This effect is least pronounced when using flood lubrication (Fig. 6b), followed closely by using LCO_2 + MQL (MoS_2) (Fig. 6e). The lack of suitable lubrication on surface finish can be seen in dry machining (Fig. 6a), LCO_2 (Fig. 6c) and LCO_2 + MQL (oil) (Fig. 6d). Material smearing in feed direction implies improper lubrication between tool and workpiece. The distance between the smearing marks coincides with feed f_z = 0.05 mm. Grooves in the direction of feed were also observed on machined surface, due to possible third body abrasion (carbide particles). Although the average roughness values of flood lubrication and LCO_2 + MQL (MoS_2) are comparable, slightly less material smearing is observed when using flood lubrication, because its use can result in lower temperature during machining compared to LCO_2 [9]. Consequently, lowest R_y value is observed for flood lubrication.

MoS_2 particles were observed on the surface of the machined workpiece (Fig. 6e, right). Average particle size of MoS_2 prior to machining was 5 µm. Particles in the size range of approx. 1 µm could be found on the surface under high magnification (3000x). The embedding of the particles into the surface seems unlikely; it is more probable that cleaning with compressed air has not completely remove all the particles from the machined surface. This is also in agreement with surface cleanliness experiments. MoS_2 particles agglomerated in grooves at the edges of the smearing tracks.

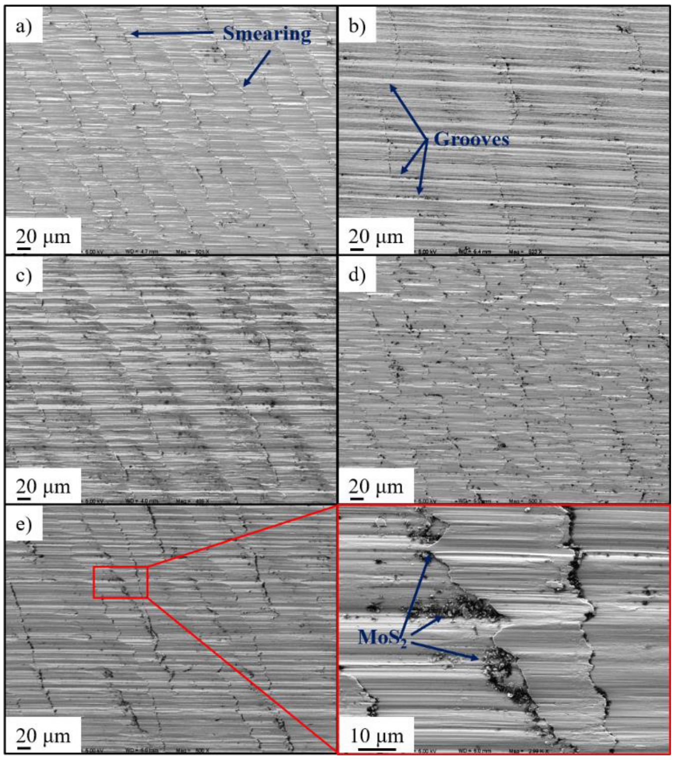

Fig. 6. Topography of machined surfaces: a) Dry machining; b) Flood lubrication; c) LCO_2; d) LCO_2 + MQL (oil); e) LCO_2 + MQL (MoS_2)

Such phenomenon did not appear homogeneously across the surface as agglomeration during delivery is also possible. However, detailed chemical analysis on these particles using Auger Eleectron Spectroscopy (AES) needs to be performed to confirm whether these particles are MoS_2 or not. The microstructure of machined surfaces parallel to feed direction is shown in Fig. 7. Deviations from ideal surface profile agree with surface topography observations and surface roughness measurements. Deformed layer thickness of approx. 1-2 µm was found to be consistent across all samples. Also, cracks on the surface were not present at any condition, even at high areas of smeared material (Fig. 6d, Fig. 7d). The use of LCO_2 + MQL (MoS_2) can provide comparable surface topography and surface layer characteristics when comparing to flood lubrication when finish milling of Inconel 718.

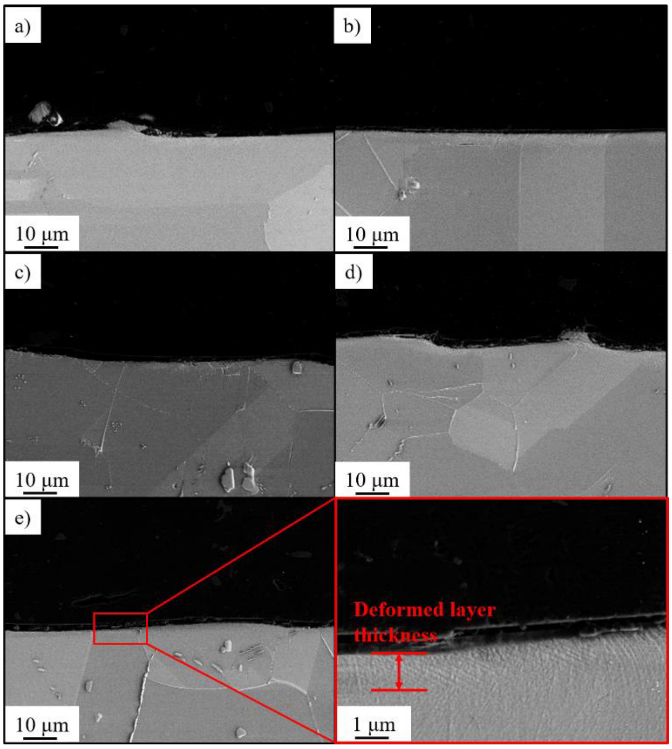

Fig. 7. Microstructure of machined surfaces: a) Dry machining; b) Flood lubrication; c) LCO_2; d) LCO_2 + MQL (oil); e) LCO_2 + MQL (MoS_2)

4. Conclusions

Five different cooling and lubrication strategies were tested in finish-milling of Inconel 718, including the recently developed strategy of lubricated LCO_2 by either oil or solid lubricant MoS_2. Under the same machining conditions (cutting parameters, new tools), the following assessments were carried out: (i) surface cleanliness after machining; (ii) surface roughness; (iii) surface topography and (iv) microstructure (affected layer thickness). The main conclusions are as follows:

- The use of unlubricated LCO_2 during machining is the closest to dry machining when high surface cleanliness after machining is desired. When using MoS_2 as a lubricant, surface cleanliness drastically improves compared to conventional MQL. Vast majority of the particles do not adhere to the surface after machining and can be easily removed.
- LCO_2 + MQL (MoS_2) achieved lower average surface roughness R_a compared to flood lubrication. Flood lubrication performed slightly better in terms of maximum height R_y. However, through tool delivery of LCO_2 + MQL (MoS_2) provided better cooling which had further positive impact on surface integrity. In this aspect, unlubricated LCO_2 and dry machining are also comparable.
- Poor lubrication during machining induced material smearing in the feed direction. Least smearing was observed when using flood lubrication, followed closely by LCO_2 + MQL (MoS_2). Small quantity of MoS_2 particles was observed on the surface after machining. Both cooling and lubrication are important for surface quality in finishing machining; MoS_2 lubricated LCO_2 can be an alternative to flood lubrication in these conditions.
- Deformed layer thickness was found to be uniform across all machined surfaces, independent of the used cooling and lubrication strategy.

Future work will include the influence of nozzle position, lubricant type and quantity on surface integrity using lubricated LCO_2. Additionally, residual stresses and microhardness analysis will be included in the future study.

Acknowledgements

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