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# Enhancement of groove turning performance by additively manufactured tool holders with internal cooling channels and combined cooling strategies

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**Abstract**

Additively manufactured machining tools allow new concepts for internal cooling channels. Commercially available grooving tool holders with two connected channels carry fluids to the cutting zone and tool flank. This study compares commercial and newly designed tool holders. The new design provides two separate channels with the option to carry different media to the primary and secondary cutting edge. Different cooling strategies (flood cooling (FC), cryogenic cooling (LN2), minimum quantity lubrication (MQL), and combinations of them) were performed on the material Ti-6Al-4V (3.7165) to validate the performance and lifetime increase of the tool inserts. The test results show that the secondary edge cooling as well as combined cooling strategies reduce wear by up to 12 %. Neither LN2 nor LN2 combined with MQL are suitable for this process and tool design, but the combination of FC and MQL leads to a cutting length greater than 10000 m at 20 % higher productivity and the same reproducible surface roughness $R_z$ of approx. 1 µm compared to commercially available grooving tool.

*Keywords:* Grooving, Cooling Lubrication Strategies, Laser Powder Bed Fusion (LPBF)

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**Nomenclature**

| | |
|---|---|
| ACS2 | Grooving tool with one fluid supply |
| ACS4 | Grooving tool with two different fluid supplies |
| FC | Flood Cooling |
| MQL | Minimum Quantity Lubrication |
| LN2 | Cryogenic cooling with liquid nitrogen |
| $v_c$ | cutting speed |
| f | feed |
| $l_c$ | cutting length |
| $VB_{max}$ | maximum flank wear |

## 1. Introduction

In the aerospace industries, hard-to-cut alloys such as titanium (high strength to weight ratio) and nickel-based alloys (high temperature strength) are often used for structural or engine components [1,2]. Both materials are challenging in machining due to their high strength and low thermal conductivity. Heat from the process is poorly dissipated, increasing the thermal load on tools and increasing wear. To increase tool life, productivity is reduced by lowering feed and cutting speed [1,3]. For heat dissipation and thus to increase productivity, cooling media are used. The best heat dissipation is achieved by a tool-integrated coolant supply that distributes the media directly to the cutting zone instead of spraying it onto the machining zone from the outside, as it is often the case [4].

Studies in grooving have shown that cooling the primary cutting edges (rake and flank face) significantly increases the life of the tool inserts due to better thermal energy removal and chip removal. In addition, the flank face cooling influences the surface quality of the workpiece decisively [5].

The internal channels are often manufactured by drilling. This limits the design freedom of the tools and prevents a flow-optimized design of the channels. Manufacturing the tools additively reduces these design limitations [6].

The Karl-Heinz Arnold GmbH already sells additively manufactured tools with internal cooling channels and a cutting width of 3 mm for groove turning. There are two systems available, which consist of a conventionally produced tool holder with drilled internal channels and two different additively produced modules, which accommodate the tool insert. The module ACS2 distributes the media to the tool's rake and flank face. The medium outlet is shaped as a triangle in order to guide the cooling medium over the entire width of the flank face and directly to the flank edges. Hence, the service life of the cutting inserts increases. The prototype module ACS4 has additional channels to supply the cutting edges [7]. The properties of the ACS2 module have so far only been considered in the developing master's thesis. Further scientific studies are still pending.

The design of a new tool holder allows to guide two different media to the cutting zone with the ACS4. This allows to combine the advantages of different media and may eliminate their disadvantages. Studies have shown that the use of minimum quantity lubrication (MQL) during drilling, turning, and milling reduces friction and thus reducing cutting forces. However, cooling is reduced compared to flood cooling (FC) [8]. Alternatively, an effective increase in cooling performance can be achieved by using cryogenic cooling with liquid nitrogen (-196 °C) (LN2) [9]. The low temperature reduces the chemical reaction between cutting and workpiece material and lowers thermal wear [10]. As a result, up to four times longer tool lives have been achieved, e. g. when cutting stainless steel [11]. The disadvantage is the poorer lubrication compared to FC and MQL. The combined cooling strategy MQL and LN2 merges a low lubricant consumption with great cooling properties. Therefore, this combination is interesting for environmentally friendly machining at a longer tool life [12].

The aim of this work is to investigate the influence of different cooling strategies on the productivity and tool life. In a first step, a tool holder with two media fittings is designed and manufactured to distribute different media to the primary and secondary cutting edges. Second, the new possibilities of combined cooling media in the cutting zone are proven and compared to the ACS2 module. Furthermore, the effect of FC, MQL, LN2, and combinations of them at different cutting speeds and feeds on tool life and workpiece surface is examined, to prove the advantages of combined cooling strategies for this process.

## 2. Experiments

### 2.1. Tool Holder and Modules

The tool holder was designed and manufactured in the laser powder bed fusion process because the media supply hole positions of the modules should not be changed and sharp edges through drilled holes meeting each other should be prevented. Tool holder and modules were manufactured on an SLM280HL machine from SLM Solutions using the material 1.2709.

The outlets of the primary exit nozzles are called C1/2 (figure 1, red) and the nozzles for the secondary edges C3/4 (figure 1, blue). The outlet of C3/4 is designed to be in a straight line to the cutting corner.

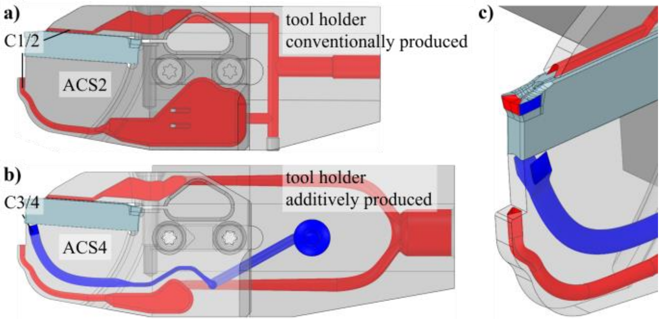

Figure 1. a) ACS2 Tool setup with conventionally produced tool holder,
b) ACS4 tool setup with additively produced tool holder
c) Sketch of cooled tool insert zones

### 2.2. Experimental setup

Orthogonal cut-off tests were carried out to determine the insert life under different cooling strategies, cutting speeds, and feed rates. 2 mm thick discs were cut from 90 mm long Ti-6Al-4V bars with a diameter of 40 mm on a vertical lathe V100 from INDEX-Werke GmbH & Co. KG. The bar was clamped 25 mm into turned-out jaws. The cutting length $l_c$ for one orthogonal cut-off operation is calculated as an Archimedean spiral. Due to the high price of the material it was not possible to repeat the tool life tests to statistically validate the results within the scope of these investigations.

The process forces in X, Y, Z direction were measured using a Kistler 9257B dynamometer. In this work the average cutting forces of the whole process excluding the entering and leaving of the tool insert were analyzed.

The maximum flank wear ($\mathrm{VB}_{\mathrm{max}}$) was measured in macroscopically captured pictures of the TiAlN coated carbide tool inserts SA35-3003N-T1 AP5020 from Karl-Heinz Arnold GmbH. Subsequently, the surface roughness was measured on the planned surface of the bars. For this purpose, three measurements according to DIN EN ISO 4288 were taken 10 mm from the center of the disc at an angle of 120 degrees with a measuring length of 4 mm. The MarSurf GD perthometer from Mahr GmbH was used for the measurement. Mean value and standard deviation are shown in the results.

### 2.3. Investigated media

**Flood Cooling:** A mixture of 10:1 of water and AVILUB Metacool oil was used and provided to the tool with a pressure of 8 bar.

**MQL:** AVILUB Metacool oil was mixed with compressed air through Laval nozzles in a LSJ Z3O from HPM technologies. The device was operated with 5 bar air pressure.

The output provided to the cutting zone was measured with an ifm SD6000 flow meter.

**LN2:** To carry liquid nitrogen to the cutting zone, it is first pumped from the supply tank with 5 bar air pressure through a sub cooler as presented in [13]. The sub cooler consists of a tank filled with liquid nitrogen at environmental pressure. A copper spiral, hung in the tank, feeds the nitrogen to the tool.

### *2.4. Experimental designs*

The tests are based on the manufacturer's recommended process parameters ($v_c = 50$ m/min, $f = 0.06$ mm/rev) for the inserts and material used. First, tool life curves for the cooling strategies FC+FC, FC+MQL were observed with the newly designed tool holder and module ACS4. Furthermore, a curve was recorded only with FC on C1/2 and with the established system ACS2 to exclude the influence of the tool system and to compare the overall performance.

With regards to the high tool lifetime, tests were also observed at a higher cutting speed ($v_c = 80$ m/min) and with LN2 cooling strategies. To compare the influence of the cutting speed on the different cooling strategies, curves at recommended and higher cutting speed at the same feed were recorded for 60 to 95 cut-offs. Tests with MQL on C1/2 were not carried out because it was assumed that the compressed air cannot remove the chip sufficiently and the process then becomes unstable. All experiments are listed in table 1.

Table 1. List of experiments

| Module | Fluid C1/2 | Fluid C3/4 | $v_c$ in m/min | f in mm/rev |
|---|---|---|---|---|
| ACS4 | FC | FC | 50 | 0,06 |
| ACS4 | FC | - | 50 | 0,06 |
| ACS4 | FC | MQL | 60 | 0,06 |
| ACS2 | FC | | 50/80 | 0,06 |
| ACS4 | FC | FC | 50/80 | 0,06 |
| ACS4 | FC | MQL | 50/80 | 0,06 |
| ACS4 | LN2 | LN2 | 50/80 | 0,06 |
| ACS4 | LN2 | MQL | 50/80 | 0,06 |
| ACS4 | FC | - | 50/80 | 0,06 |

## 3. Results

### *3.1. Comparison of ACS2 and ACS4 tool system performance*

The tool life curves of the first four experiments show a similar trend for the different cooling strategies. During the first approx. 2000 m cutting length, the maximum wear increases continuously and then remains constant. From a cutting length of 8000 m onwards, the wear increases again followed by an increase of feed force only at the ACS4 test setup without secondary cutting edge cooling, describing the end of the tool life, figure 2a, c. Accordingly, the tool life of the inserts is increased by the additional media supply to the secondary cutting edge.

Based on the results of a small screening test plan, the cutting speed of the FC+MQL cooling strategy was set to 60 m/min – compared to 50 m/min in the other tests. Nevertheless, the maximum wear is identical compared to the other tests and an end of tool life cannot be detected even after 10000 m cutting distance, figure 2a. Thus, we recommend the combined cooling strategy FC+MQL for cut-off turning. It promises the same tool life with 20 % higher productivity compared to plain FC.

The analysis of the measured surface roughness shows that it becomes stable after approx. 3000 m for the first time for all tests. An opposite trend is observed between the different tests. In the tests with the ACS4 module without secondary cutting edge cooling, the value continues to increase and then remains relatively constant, figure 2b. A possible explanation is that small particles of the chips are not ideally removed from the cutting zone and settle in the exit nozzles from which no medium is supplied. These particles scratch the workpiece surface. This theory also supports the observed varying feed forces as particles repeatedly detach and then rub between the workpiece and the tool. However, a correlation between measured insert wear and measured forces cannot be detected, figure 2b, c.

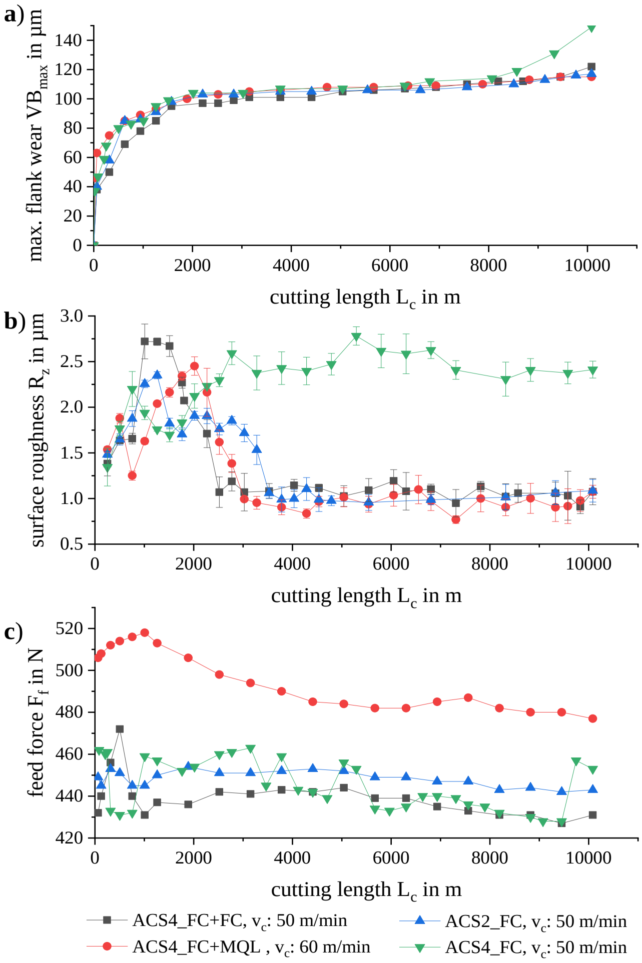

Figure 2. a) max. flank wear $VB_{max}$ b) surface roughness $R_z$ c) feed force $F_f$ over cutting length $L_c$

### *3.2. Influence of cutting speed and cooling strategies on tool life*

Figure 3 shows the results of the different cooling strategies at different cutting speeds. Except for LN2+MQL, only small differences in wear and forces are observed between the cooling strategies at a cutting speed of 50 m/min. It is observed that the wear is 12 % lower when using FC for primary and secondary cutting edge cooling than without secondary cutting edge cooling. However, the wear increases continuously and reaches comparable magnitudes for all cooling strategies after a cutting length of 1260 m.

The comparison of the results of ACS4_FC and ACS2_FC show that the lateral outlet channels have a negative influence if they are not supplied with a cooling lubricant at higher cutting speed. Again this could be explained by particles of the chips that are not ideally removed from the cutting zone and settle in the exit nozzles. However, no proof for this hypothesis could be found.

When ACS2_FC is compared with ACS4_FC+FC, the strengths of secondary edge cooling are apparent. The wear on ACS4_FC+FC increases slowly after approx. 1200 m, whereas on the ACS2_FC test setup the wear increases rapidly to the point of tool insert breakage.

The analysis of the combination of FC+MQL shows a positive effect especially at higher cutting speeds. Wear remains constant up to a cutting length of 2000 m, figure 3b. The good performance of the cooling strategy is attributed to the improved lubrication and thus reduced feed forces, figure 3d. In contrast, the reduced cooling performance of the cooling strategy is visible at higher cutting speeds. Especially when the wear pattern is compared to FC+FC a stronger discoloration of the insert is noticeable, figure 4. Nevertheless, the combination seems to be a promising approach as no progressive wear increase can be observed even after $l_c$ = 2000 m.

The analysis of the wear pattern of LN2 fed to all cutting edges, shows that it is only loaded in the cutting zone. The rest of the surface shows no discoloration like the inserts of the other strategies, figure 4. This means, there is no thermal load. As observed by [10], this suggests that there is no chemical reaction between the coating and the workpiece. The very uniform wear pattern, which appears to occur only on the surface, also supports the conclusions of [9], that the evaporating LN2 forms a gas cushion and thus reduces the contact area. The low wear is therefore a result of excluding the mechanisms' diffusive wear, adhesion, and high temperature oxidation. At low cutting speeds, this results in the best wear pattern. This effect seems not to apply at higher cutting speeds. At the cutting edges there is a progressive strong abrasive wear, figure 4. This is also reflected in significantly increased wear growth and thus feed forces, figure 3b, d.

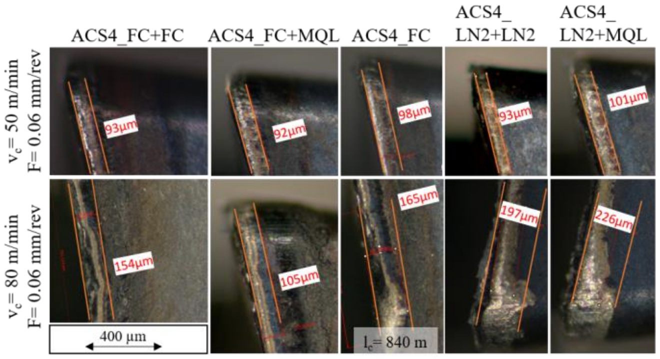

Figure 4. Flank wear after $l_c$ = 1260 m at different cooling strategies and cutting speed

Last, the LN2+MQL cooling strategy is analyzed. At both, low and high cutting speeds, highest wear and feed forces occur, figure 3. This can be explained by two aspects. Firstly, the liquid nitrogen freezes the tool. The oil droplets of the MQL aerosol initially emerge from the outlet as small lumps with a volume flow of 27.2±0.6 Nl/min, figure 5a. Secondly, the oil

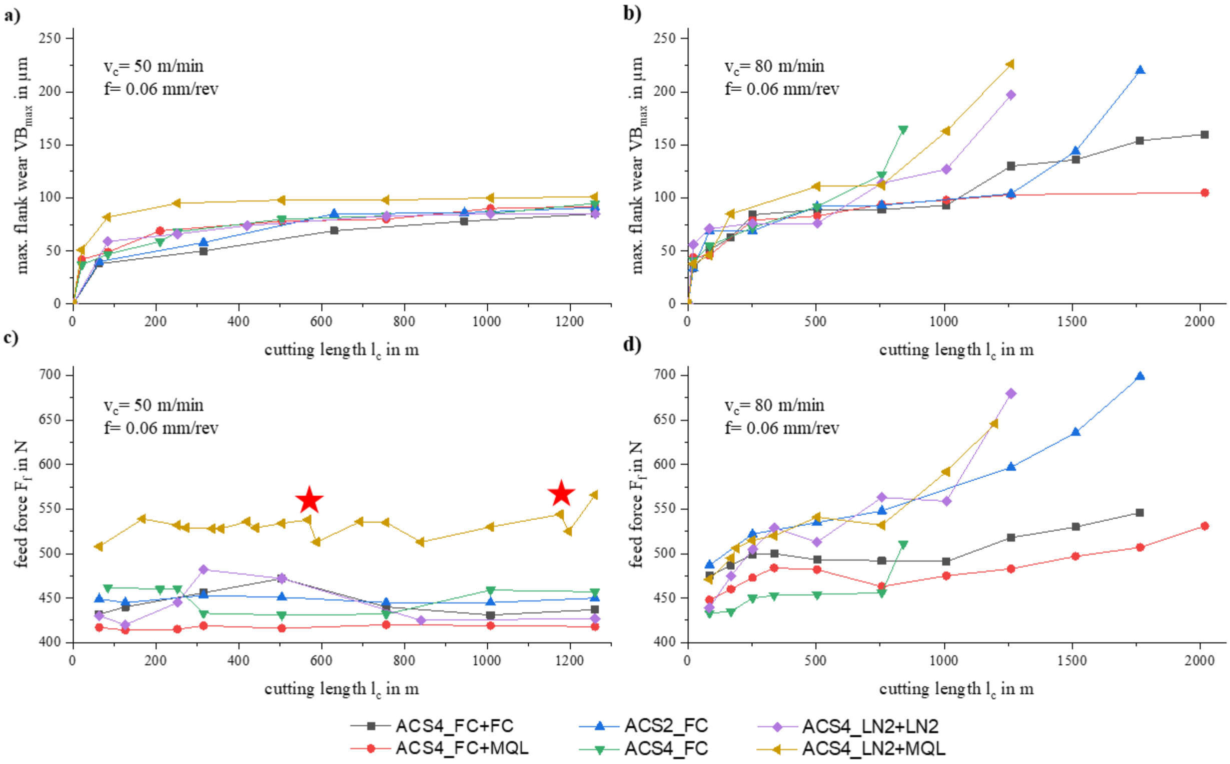

Figure 3. a,b) maximum flank wear and c,d) feed force for different cooling strategies

condenses on the cold channel walls. This clogs the nozzle exit leading to an abrupt decrease in MQL volume flow to 9.4±0.2 Nl/min, even with increased operating pressure of the MQL supply to 7 bar and the process running. Thus, the volume flow is 92 % lower than with the combination of FC+MQL with 75.2±3.9 Nl/min, figure 5b.

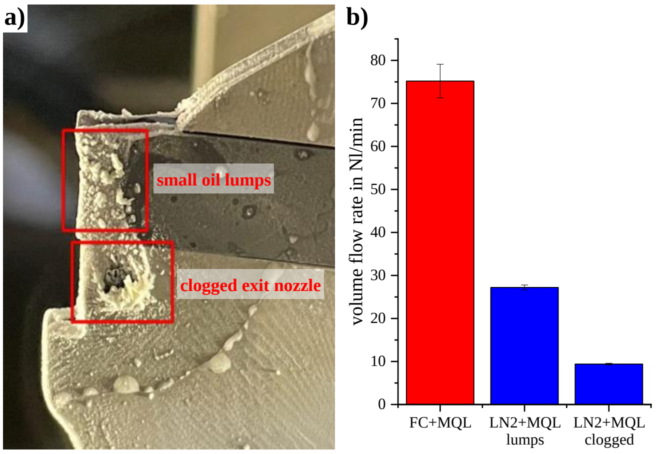

Figure 5. a) MQL oil freezing when operated with LN2 b) MQL volume flow rate when used with FC or LN2

Because of this problem, the channels were defrosted with a heat gun (figure 3c, red markings) in order to further investigate the cooling strategy. This process intervention gives the ability to blow the oil back into the cutting zone, which repeatedly decreases the feed force, figure 3c. Since defrosting the tool showed no effect on wear, this was not carried out further. Additionally, in production this is not a robust process, meaning a combination of LN2+MQL is unsuitable for tools without a thermally separated media supply. This is also attributed to the results of [14], who found a significant increase in tool life when milling titanium with LN2 and MQL applied through two separate nozzles.

The wear and feed force of ACS4_LN2+MQL with frozen exit nozzles and ACS4_LN2+LN2 are very similar at higher cutting speeds. From this observation and the positive results of the ACS4_FC+MQL tests, it is concluded that the lubrication of the secondary cutting edges is crucial for a long tool insert life at higher cutting speeds.

### *3.3. Observed optimization potentials of the new tool ACS4*

The new design and production of the additive tool holder and ACS4 module still need to be optimized. During the tests, the transition between the module and the tool holder did not seal ideally and media leaked laterally over the sealing surface. Furthermore, only one ACS4 module out of twelve provided a subjectively assessed usable spray pattern and was used for all tests. This assumes a consistent quality of the media flow over the investigations, making the results comparable. Some of the exit nozzles of the other modules did not provide any media flow. This suggests that the position of the media supply holes from module to tool holder was not ideal for all modules. In addition, the volume flow of media appeared to be lower, superimposed by a partially pulsating outflow compared to the ACS2 test setup. This indicates that the additive manufacturing of the inner channels is not yet ideally adjusted and the flow is generally disturbed. Therefore, before the cutting tests, attention was paid to a continuous media outlet. However, if the new concept is further optimized and brought to the same level of development as the ACS2 setup, the results let expect that the tool life can be significantly increased by the additional media supply to the secondary cutting edge.

## 4. Conclusion

In this work a new additively manufactured grooving tool system was designed to distribute two different media to the primary and secondary cutting edges. The system is based on the already available conventionally manufactured tool holder and additively produced ACS2 grooving tool of Karl-Heinz Arnold GmbH. The newly developed and already available systems were compared with each other. It was investigated which influence different cooling media have on the productivity, tool life, and surface roughness of the workpiece. It was found that the new tool setup must be further designed and optimized. At this point the new module is as good as the one already available at low cutting speed and better at higher cutting speed. The following results show the advantages of the new design even if there are still there is potential for improvements:

- Wear decreases up to 12 % when using secondary cutting edge cooling with flood cooling supply to all cutting edges.
- Hybrid cooling strategies with flood cooling on the primary cutting edges and minimum quantity lubrication on the secondary cutting edges lead to increased tool life at 20 % higher cutting speed compared to recommended 50 m/min. A higher cutting speed of up to 80 m/min could also work with a long tool life, but needs further investigation.
- Hybrid cryogenic cooling strategies need thermally separated media supplies to prevent freezing of the other media even during a running process.
- Stable surface roughness results need a working-sharp tool insert. From this point a surface roughness of approx. 1 µm $R_z$ is possible.

## 5. Acknowledgements

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