Investigation of the influence of carbon dioxide cryogenic cooling on surface pollution, surface roughness and tool wear during turning

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Abstract

Oil-based cutting fluids in machining are not only a burden for the environment, but also pollute the machined workpieces with residues. Cryogenic media such as carbon dioxide ($\text{CO}_2$) are established incrementally as a cleaner alternative to conventional cooling lubrication methods. For this reason, this article investigates the suitability of $\text{CO}_2$ as a coolant for turning of materials such as Copper OFE, Stainless Steel 316LN (SS 316LN) and Niobium high RRR, which are used at CERN for a wide range of accelerator components e.g. radio-frequency (RF) cavities and ancillaries. They are examined with regard to surface pollution, surface roughness and tool wear. The tests concerning surface pollution show that $\text{CO}_2$ does not leave any residues on the workpieces surface and is therefore suitable for ultra-high-vacuum (UHV) applications. The tests regarding surface roughness show an improvement of the surface quality of all investigated materials compared to the tested conventional cooling methods emulsion, alcohol and straight oil. In contrast, in the investigation of tool wear, the performance of emulsion cooling could only be achieved with the addition of a minimum quantity of oil.

Cryogenic Machining, Surface Integrity, Tool wear, Clean Machining

1. Introduction

The failure of machined parts due to wear, corrosion and fatigue often starts at the surface of the manufactured workpieces. In machining numerous factors determine the outcome of a surface and cutting fluids in particular have a significant influence on it [1]. In this context, the use of cryogenic media for cooling and lubrication during the cutting process has proven to be an environmental-friendly method that has the potential to improve surface integrity, avoid contamination of the workpiece surface and also increase tool life over conventional cooling methods [2] [3].

There are various cryogenic coolants on the market, but liquid nitrogen (LN$_2$) and $\text{CO}_2$ are the most common ones. LN$_2$ boils at a temperature of -195.8 °C at atmospheric pressure. For machining applications, special measures such as the insulation of the spindle and coolant channels are necessary. $\text{CO}_2$, on the other hand, is less complex to handle and can be stored by keeping it under high pressure in gas cylinders. At atmospheric pressure it expands and is then converted into 40 % snow and 60 % gas with a temperature of -78.5 °C [3]. Although $\text{CO}_2$ is a greenhouse gas, industrial applications usually use recycled $\text{CO}_2$ from other processes, which means that it does not add to the environmental burden [4].

Milling studies with LN$_2$ were carried out by Shokrani et al. [5] on Inconel 718. He reported a reduction of $R_a$ of 33 % when comparing LN$_2$ and dry machining. Nevertheless, this effect was reversed with increasing machining time and the roughness values became much worse under cryogenic cooling, as tool wear increased significantly. Çakir et al. [6] compared $\text{CO}_2$, emulsion and dry machining while turning of AISI1040 steel. The experiments showed a surface roughness for $\text{CO}_2$ which was slightly better than for emulsion and significantly better than for dry machining.

Wstawska et al. [7] has conducted a literature review on the cryogenic machining of titanium alloys and concluded that the use of cryogenic coolants shows great potential to improve tool wear. In contrary, Tapoglou et al. [4], who investigated tool wear progression during milling of Ti-6Al-4V, reported differently. In those experiments emulsion coolant performed better than $\text{CO}_2$. Additionally, he reported that the performance of $\text{CO}_2$ regarding tool wear can be improved by combining it with Minimum Quantity Lubrication (MQL).

The literature research shows that while there is a wide variation in results, depending on the selected machine parameters, tools and materials, there is great potential to improve workpiece quality and tool wear by using cryogenic media. For this reason, it is worthwhile to further investigate a possible replacement of conventional cutting fluids for certain applications.

The purpose of the article is to evaluate the performance of cryogenic coolant for finishing machining applications. Therefore, experiments are carried out to compare its machining performance with the conventional cooling methods emulsion, straight oil and alcohol. The tests are designed to investigate the surface contamination caused by cutting fluids, the surface roughness after finishing and the tool wear. The aim is mainly to provide a solution to the need of reworking clean parts for UHV-applications, where any kind of surface contamination is prohibited.

The materials under investigation are SS 316LN, Copper OFE and Niobium high RRR. The experiments will be carried out on a lathe and as cryogenic medium $\text{CO}_2$ is used, because of its suitability for a flexible and cost-effective integration into an existing machine environment.
2. Experimental Setup

The machine used for the studies is a CNC turning machine of the CMZ TA Series. Regarding tooling the cutting insert VCGT160404-AK H01 is used for the Copper OFE and Niobium high RRR samples and the VBM160404-MM 2035 for SS 316LN. For the CO₂ cooling the mobile cryogenic system AEROSOL MASTER 4000cryolub by Rother is used. The system provides an aerosol oil mixture in combination with CO₂ which can be used in different ratios. The injected CO₂ rate can be adjusted from 0 to 100 %, the compressed air pressure from 0 to 7.5 bar and moreover oil for micro spraying can be added in different levels. The CO₂ supply is provided by a rack with twelve bottles and the cooling lubricant can be fed into the cutting zone through two nozzles which can be installed in the machine turret, illustrated in Figure 1. The nozzles are positioned in a way to guide the CO₂ to the rake and flank face.

![Figure 1](image1.jpg)

Figure 1. Positioning of the two CO₂-nozzles during turning tests

The conventional cooling lubricants emulsion, alcohol and the cutting oil Vascomill HD 20 [8] are used for comparison. Ethanol represents the current solution for clean machining without surface residues. The emulsion is provided directly by the machine supply. Ethanol and Vascomill are manually injected into the cutting zone.

3. Experiments

3.1 Surface Pollution

In order to test the pollution effects of CO₂-cooling, a test chamber is machined of SS 316LN with pure CO₂ as cutting fluid. It is subsequently cleaned by the CERN cleaning method for UHV-applications [9]. To measure the gas species which are present on the workpieces surface, a Residual Gas Analyzer (RGA) is used.

The diagram in Figure 2 shows the ion current of the molecules found on the surface of the SS 316LN samples. It includes the limit for UHV-applications, the values of the test background and the measured values of the test chamber.

![Figure 2](image2.jpg)

Figure 2. Ion current of the molecules found on the surface of the SS 316LN sample by RGA

It can be observed that that only peak 26 reaches the limit and peak 31 is above the limit. However, since this is also the case for the background, the peaks can be attributed the test bench. The surface contamination caused by CO₂ machining is therefore within the allowed limit and it is thus a suitable method for UHV-applications.

3.2 Surface Roughness

The tests to compare the surface roughness after finishing are carried out for all the aforementioned materials. The values are measured after face turning, which is relevant for the machining of ancillary components such as flanges for RF-applications. For the examined cutting parameters, the feed rate \( f_2 \) and cutting depth \( a_2 \) are kept constant and the cutting speed \( v_c \) is varied by about ±20-30 % compared to the reference condition of the respective material. The exact test matrix is shown in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>( v_c ) [m/min]</th>
<th>( f_2 ) [mm/tr/dent]</th>
<th>( a_2 ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 316LN</td>
<td>110</td>
<td>140</td>
<td>80</td>
</tr>
<tr>
<td>Copper OFE</td>
<td>100</td>
<td>130</td>
<td>70</td>
</tr>
<tr>
<td>Niobium high RRR</td>
<td>60</td>
<td>80</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cutting Speed [m/min]</th>
<th>( R_p ) [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>3.0</td>
</tr>
<tr>
<td>80</td>
<td>2.0</td>
</tr>
<tr>
<td>140</td>
<td>1.0</td>
</tr>
</tbody>
</table>

![Figure 3](image3.jpg)

Figure 3. \( R_p \) on the face of machined SS 316LN samples under CO₂, alcohol and emulsion cooling

For Copper OFE there seems to be a low sensitivity to the type of lubricant (Figure 4). CO₂ gives comparable results to alcohol and emulsion. Only for the \( R_p \) at lower cutting speed a clearer difference between the cooling lubrication types is visible and emulsion cooling reaches a much better result than CO₂ or alcohol. In addition, CO₂ appears to be again much less sensitive to variation in cutting speed than alcohol. Nevertheless, the surface for CO₂ improves slightly with increasing cutting speed. This may be a sign of a shift in the thermal balance of the cut.
To evaluate the deviation error, the extra high oil supply in the cutting zone is recorded with a microscope (Leica DMS1000) and the surface roughness on the stainless steel bar is measured with the portable roughness meter. The measurements are conducted without removing the tool holder or workpiece from the machine to avoid deviation error. In total 22 minutes are machined. The first test is carried out with pure CO\textsubscript{2}, as this is expected to be the most critical due to the lack of lubricating effect, which is why its performance has to be evaluated first. The same tests, with fewer measurements, are then repeated for emulsion and the other CO\textsubscript{2} configurations. After the 22 minutes the condition of each insert is further examined with a Zeiss Scanning Electron Microscope (SEM) in order to investigate the wear mechanisms.

Figure 6 shows the development of the measured surface roughness \(R_z\) with increasing machine time. The values for emulsions and CO\textsubscript{2} cooling with air and oil are significantly lower and the progression of the curves is softer than for pure CO\textsubscript{2} or CO\textsubscript{2} with air. What is also noticeable is the large peak for CO\textsubscript{2} plus air cooling. The profile of the machined surface shows discontinuity with defects such as particle adhesion. This depicts, especially by comparing it with the previous surface roughness tests, that the process cooling with CO\textsubscript{2} is not yet stable and reliable.

3.3 Tool wear

For the investigation of tool wear different CO\textsubscript{2} configurations are compared with emulsion cooling. Therefore, pure CO\textsubscript{2} is tested as well as with the addition of compressed air and with compressed air and oil. The tests are carried out with a bar of SS 316LN, from which material is removed on the diameter under the aforementioned reference cutting conditions.

After a specific machining time the condition of the cutting insert is recorded with a digital microscope (Leica DMS1000) and the surface roughness on the stainless steel bar is measured with the portable roughness meter. The measurements are conducted without removing the tool holder or workpiece from the machine to avoid deviation error. In total 22 minutes are machined. The first test is carried out with pure CO\textsubscript{2}, as this is expected to be the most critical due to the lack of lubricating effect, which is why its performance has to be evaluated first. The same tests, with fewer measurements, are then repeated for emulsion and the other CO\textsubscript{2} configurations. After the 22 minutes the condition of each insert is further examined with a Zeiss Scanning Electron Microscope (SEM) in order to investigate the wear mechanisms.

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When observing the flank wear evaluation in Figure 7 and the microscopy pictures of the used cutting inserts in Figure 8 and 9 a possible reason for the higher \(R_z\)-values can be found. As seen in the flank view images, all the used inserts exhibited flank and notch wear. In the diagram and in the pictures (Figure 8 and 9) it can be seen that the worn area is generally slightly larger in the specimen with only CO\textsubscript{2} cooling and with CO\textsubscript{2} and air cooling. The higher tool wear may affect the quality of the machined surface.

Besides, especially the insert which is only used with 100 % CO\textsubscript{2} shows considerably more build up edge (BUE) than the others. BUE tendency is known to be reduced with increasing temperatures in the cutting zone. Thus, this effect can be attributed to the low temperatures while machining with pure CO\textsubscript{2}. Comparatively high notch wear is also visible on the SEM-images, which is enhanced by BUE. Another effect that can be observed is the chipping on the tool tip. Again, it is mainly the
inserts which are CO₂-cooled without additional lubrication that are affected. Overall, it can be observed that the flank wear decreases with increasing oil proportion in the cutting fluid, which can be traced back to the higher mechanical load due to the higher friction. Hence the wear and abrasion for emulsion or CO₂ with compressed air and oil is less than for pure CO₂ or CO₂ with compressed air only. CO₂ in combination with compressed air and oil shows the lowest wear, which is probably due to the lubricating effect combined with the low temperatures caused by CO₂, since flank wear is a mainly temperature driven phenomenon. The results emphasize the dual purpose of coolants: both the cooling and the lubricating of the cutting zone must be ensured in order to dissipate the produced heat and extend tool life.

Figure 8. Flank view of the investigated cutting inserts by microscopy after machining for 22 min of SS 316LN under 100 % CO₂ emulsion, 100 % CO₂ + 2.5 bar air and 100 % CO₂ + 2.5 bar air + 2.6 bar oil cooling

Figure 9. Flank and nose view of the investigated cutting inserts by SEM after machining 22 min of SS 316LN under 100 % CO₂ emulsion, 100 % CO₂ + 2.5 bar air and 100 % CO₂ + 2.5 bar air + 2.6 bar oil cooling

4. Conclusion

In this article surface pollution, surface roughness and tool wear during cryogenic machining with CO₂ and conventional coolants have been investigated and compared during turning operation. The purpose was to investigate the suitability of CO₂ cooling for the finishing operation of SS 316LN, Copper OFE and Niobium RRR, with special focus on residue-free machining. The conclusions and outlooks are as follows:

- The examination of surface contamination clearly shows the suitability of CO₂ for UHV-applications. Further tests, which also check the degree of contamination of CO₂ in combination with compressed air could be beneficial, to be able to produce clean workpieces with the best possible surface quality.
- The surface roughness tests show a CO₂ performance, which is comparable to or even better than conventional coolants. It is also shown that the used reference cutting parameters, which work well for other cutting fluids, do not necessarily produce the best possible results for CO₂ machining and still need to be adjusted.
- Regarding the tool wear tests, it could be observed that the stand-alone-method with pure CO₂ seems to be only suitable for finishing operations and that additional lubrication is required for longer machine times to ensure sufficient workpiece quality. However, in order to verify these results, tests should be carried out on other materials as well and the course of tool wear should be further observed over extended machining times.

Hence, cryogenic machining with CO₂ offers more than just a clean process but has the capability to improve the final part performances through enhanced machined surface quality. Nevertheless, the successful performance of cryogenic machining is dependent on a number of factors, which need to be investigated further.

References