euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020
www.euspen.eu

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 (CO_2) are established incrementally as a cleaner alternative to conventional cooling lubrication methods. For this reason, this article investigates the suitability of 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 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 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. 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 CO_2 is a greenhouse gas, industrial applications usually use recycled 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 CO_2, emulsion and dry machining while turning of AISI1040 steel. The experiments showed a surface roughness for 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 CO_2. Additionally, he reported that the performance of 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 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 VBMT160404-MM 2035 for SS 316LN. For the CO_2 cooling the mobile cryogenic system AEROSOL MASTER 4000cryolub by Rother is used. The system provides an aerosol oil mixture in combination with CO_2, which can be used in different ratios. The injected CO_2 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 CO_2 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 on the machine turret, illustrated in Figure 1. The nozzles are positioned in a way to guide the CO_2 to the rake and flank face.

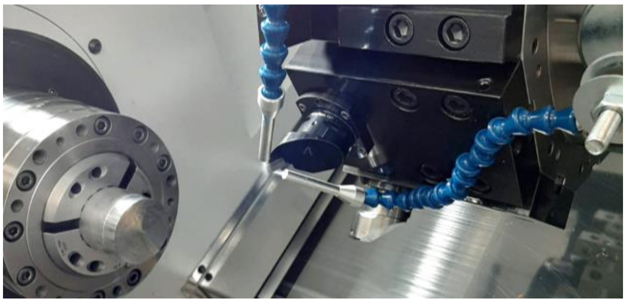

Figure 1. Positioning of the two CO_2-nozzles during turning tests

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 CO_2-cooling, a test chamber is machined of SS 316LN with pure CO_2 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.

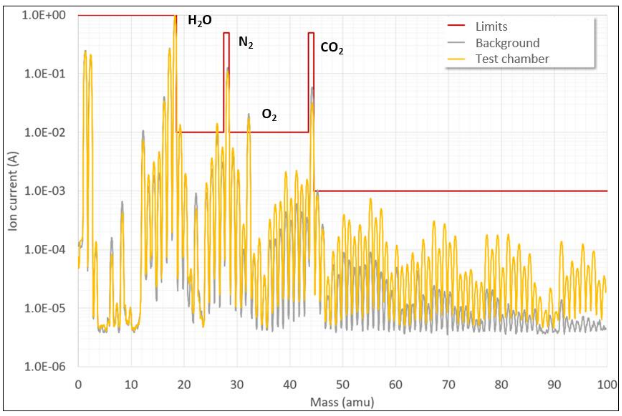

Figure 2. Ion current of the molecules found on the surface of the SS 316LN sample by RGA

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 CO_2 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_z and cutting depth a_p 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 1. Examined turning parameters for each tested material

Material	v_c [m/min]			f_z [mm/tr/dent]	a_p [mm]
	ref	v_c+	v_c-		
SS 316LN	110	140	80	0.05	0.1
Copper OFE	100	130	70	0.05	0.1
Niobium high RRR	60	80	40	0.05	0.1

Depending on the material, the tests are carried out with different CO_2 configurations, with either extra compressed air or oil being added. For the comparison, only the conventional cooling lubricants are tested on the respective material, which also represent the commonly used method for it. In addition, for many samples only the reference speed is tested with those coolants, since the suitability of the conventional methods has already been established and the tests are only intended for comparison purposes. For the measurement of the surface roughness the portable roughness meter MARSURF PS 10 is used. The values for R_a are measured on the machined surface at two points each and the average is taken.

Figure 3 shows the R_a-measurements on the face after turning SS 316LN with emulsion, alcohol and CO_2 for different cutting speeds. CO_2 seems to perform significantly better than alcohol or emulsion turning. Furthermore, the sensitivity for CO_2 with varying cutting speed is lower than for alcohol.

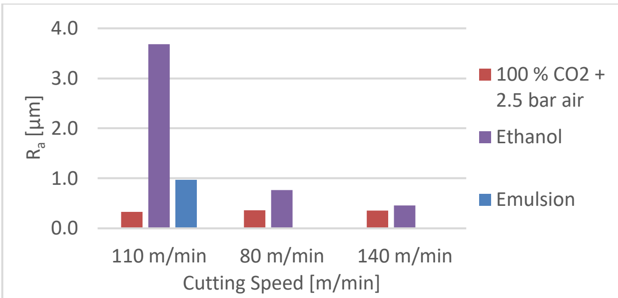

Figure 3. R_a on the face of machined SS 316LN samples under CO_2, alcohol and emulsion cooling

For Copper OFE there seems to be a low sensitivity to the type of lubricant (Figure 4). CO_2 gives comparable results to alcohol and emulsion. Only for the R_a at lower cutting speed a clearer difference between the cooling lubrication types is visible and emulsion cooling reaches a much better result than CO_2 or alcohol. In addition, CO_2 appears to be again much less sensitive to variation in cutting speed than alcohol. Nevertheless, the surface for CO_2 improves slightly with increasing cutting speed. This may be a sign of a shift in the thermal balance of the cut.

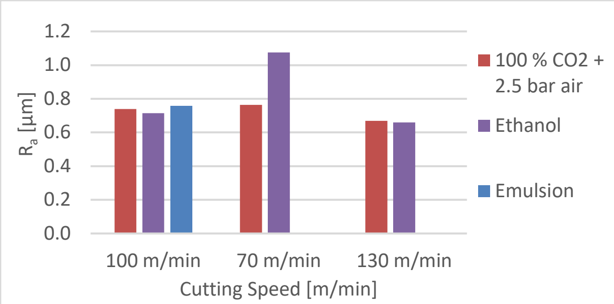

Figure 4. R_a on the face of machined Copper OFE samples under CO_2, alcohol and emulsion cooling

The Niobium high RRR samples were only tested with reference speed with different cooling lubrication methods. For the lower and higher cutting speed exclusively CO_2 is tested. The result is visible in Figure 5. CO_2 with air reaches the same R_a as the cutting oil Vascomill HD20, which is usually used for niobium machining and is lower than emulsion. The extra high oil supply positively influences the surface roughness, which can be seen both by the supply directly via the cryogenic system, recognizable by the orange bar, and manually (brown bar). It seems that in the case of niobium it is the lubricating aspect of the cutting area that is more important than the cooling aspect of the material to be machined. Besides, it can be stated that increasing cutting speed has a positive effect on R_a. The cutting speed selected as a reference for niobium may therefore be too low when machining with CO_2.

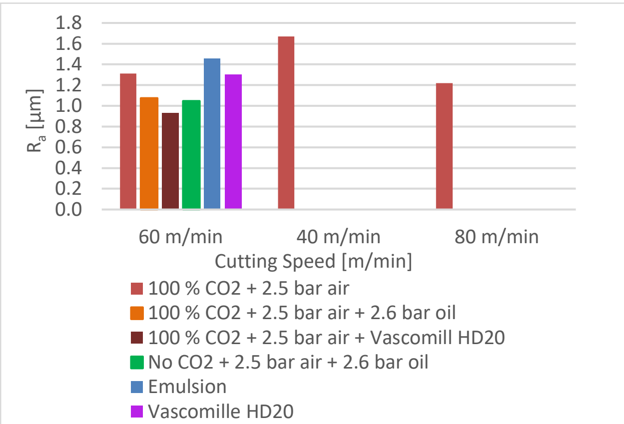

Figure 5. R_a on the face of machined Niobium high RRR samples under cooling with different CO_2 configurations, emulsion and Vascomill HD20

3.3 Tool wear

For the investigation of tool wear different CO_2 configurations are compared with emulsion cooling. Therefore, pure CO_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_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_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_a with increasing machine time. The values for emulsions and CO_2 cooling with air and oil are significantly lower and the progression of the curves is softer than for pure CO_2 or CO_2 with air. What is also noticeable is the large peak for CO_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_2 is not yet stable and reliable.

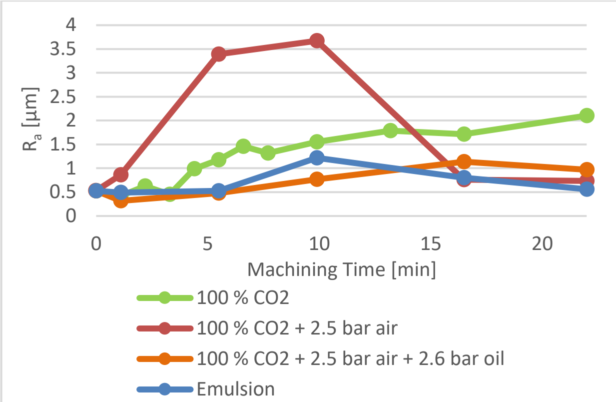

Figure 6. R_a depending on the machining time for cooling with different CO_2 configurations and emulsion while turning of SS 316LN

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_a-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_2 cooling and with CO_2 and air cooling. The higher tool wear may affect the quality of the machined surface.

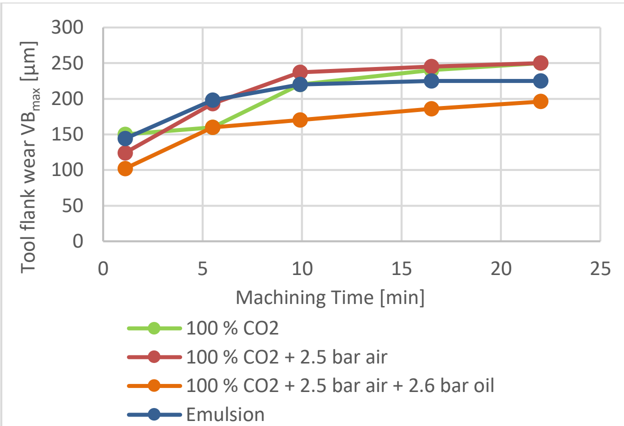

Figure 7. Evolution of flank wear VB_{max} depending on the machining time for cooling with different CO_2 configurations and emulsion during turning of SS 316LN

Besides, especially the insert which is only used with 100 % CO_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_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 CO_2-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 CO_2 with compressed air and oil is less than for pure CO_2 or CO_2 with compressed air only. CO_2 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 CO_2, 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.

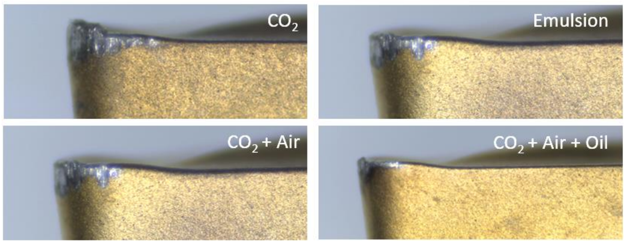

Figure 8. Flank view of the investigated cutting inserts by microscopy after machining for 22 min of SS 316LN under 100 % CO_2, emulsion, 100 % CO_2 + 2.5 bar air and 100 % CO_2 + 2.5 bar air + 2.6 bar oil cooling

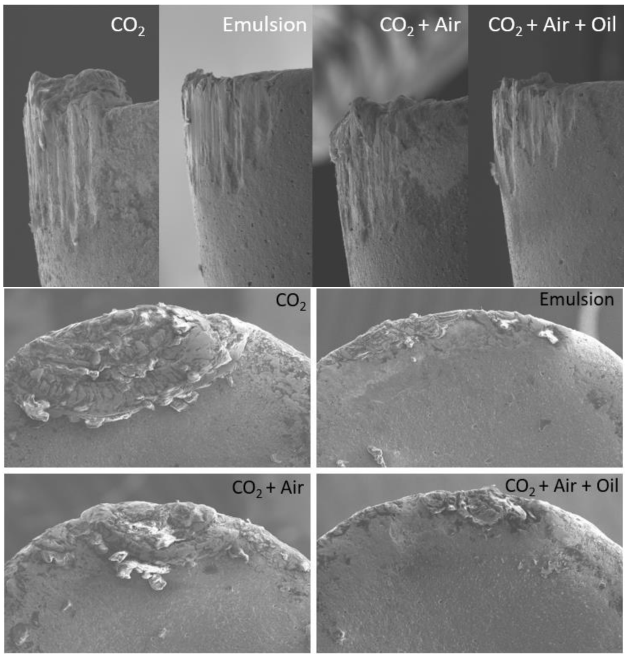

Figure 9. Flank and nose view of the investigated cutting inserts by SEM after machining 22 min of SS 316LN under 100 % CO_2, emulsion, 100 % CO_2 + 2.5 bar air and 100 % CO_2 + 2.5 bar air + 2.6 bar oil cooling

4. Conclusion

In this article surface pollution, surface roughness and tool wear during cryogenic machining with CO_2 and conventional coolants have been investigated and compared during turning operation. The purpose was to investigate the suitability of CO_2 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 CO_2 for UHV-applications. Further tests, which also check the degree of contamination of CO_2 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 CO_2 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 CO_2 machining and still need to be adjusted.
– Regarding the tool wear tests, it could be observed that the stand-alone-method with pure CO_2 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 CO_2 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.

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