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Next generation high performance cutting by use of carbon dioxide as cryogenics

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Abstract

This paper shows a new milling concept, Walter Cryo·tec™. With this concept, the internal multi-channel supply of cryogenic media as well as other media e.g. cold air, MQL or cutting emulsion by means of a special machine tool spindle and an adapted cutting tool is supported. Cutting tests with different cooling and lubrication strategies were carried out. The effects of these strategies are compared. The paper focuses on the quantification of the potential of cryogenic machining with CO_2 in milling of high temperature high strength stainless steel. The major benefits are higher cutting data, higher material removal rates and less tool wear. Besides the economic effects, the environmental advantages are shown.

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Keywords: Cryogenic machining; High performance cutting; Cutting tool

1. Introduction

First experiments with cryogenic machining have been done in the 1950s. In the 1990s, a research program founded by the NSF from the Columbia University (NY) including 12 companies from machine tool builder, automotive and aerospace industry was started in order to develop an economical cryogenic machining approach [1, 2]. Most of the research work is dealing with turning operations with supply of liquid nitrogen as cryogenic media [1, 2, 3, 4, 5, 6, 7]. Milling studies with liquid nitrogen were performed by Shokrani et al [8].

In machining processes, heat is generated due to plastic deformation and tribological effects. Plastic deformation takes places in three zones: The primary shear flow zone, the secondary sheer flow zone, and the rubbing zones on flank and rake face. Most of the energy is converted into heat [9, 10, 11]. The major wear mechanisms occurring in machining are strongly temperature-dependent. Therefore, lubricoolants are widely used in order to reduce the cutting temperatures, to reduce the wear rate and to improve the workpiece quality.

In comparison to conventional machining with flood lubrication, cryogenic cooling can be an environmental friendly alternative and can lead to higher applicable cutting parameters as well as higher tool life [12]. As these aspects are gaining more and more importance, cryogenic machining has been more focused in research and industrial application in the recent past.

2. Cryogenic machining with carbon dioxide CO_2

Most common media for cryogenic machining are liquid nitrogen LN_2 and carbon dioxide CO_2. Liquid nitrogen (LN_2) boils at $T_B = -195.8\ °C$ at atmospheric pressure, Table 1. Liquid carbon dioxide CO_2 is a refrigerated liquefied gas. At room temperature it can be held liquid by a minimum pressure of p_{min} = 57 bar, Fig. 1. It can be stored in high pressure gas cylinders. When it fuses with the ambient air, it becomes a gas

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and a solid – dry ice – and drops down to -78.5 °C due to the phase transformation.

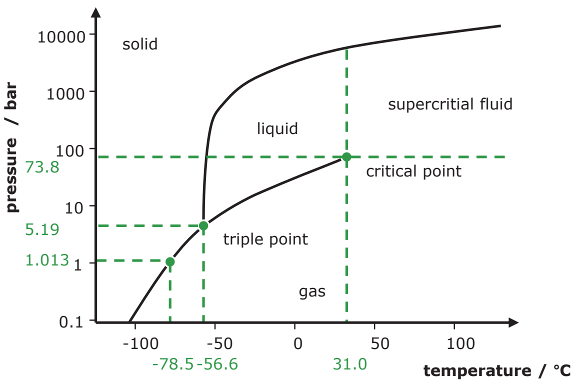

Fig. 1. Phase diagram of carbon dioxide CO_2To investigate

Table 1. Physical properties of N_2 and CO_2 compared to conventional coolants

	c_p	ΔHv	T_s	λ (25°C, 1 bar)
	$J{\cdot}K^{-1}{\cdot}kg^{-1}$	$kJ{\cdot}kg^{-1}$	°C	$W{\cdot}\ m^{-1}K^{-1}$
N_2	1.0	200	-195.8	$256.6{\cdot}10^{-4}$
CO_2	0.8	350	-56.6	
H_2O	4.2	2300	100	0.6
Mineral oil	1.9	280	150-250	0.15
Ester oil	2	338	224	1

3. Tool design for cryogenic cooling with CO_2

One essential need for an optimal process design when machining with cryogenics are special adapted cutting tools. In the Cryo·tec^{TM} tool concept for milling with liquid CO_2, two coolant exits were implemented in the cutting tool body, Fig. 2. As tool for this study a modified Walter copy milling cutter F2334R with a diameter of D_a = 50 mm and five teeth (z = 5) was used.

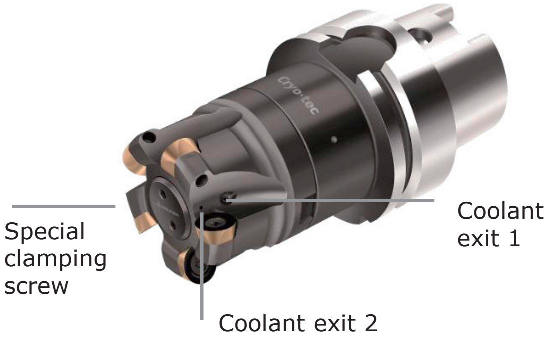

Fig. 2. Design of Cryo·tec^{TM} copy milling tool F2334R

The CO_2 and the other lubricant coolant remain separated until both media reaches the cutting zone. The tool body is characterized by two concentric coolant channels, Fig. 3. One channel can be used for the transportation of liquid CO_2, the second one for the supply of MQL or air.

As cutting tool material, uncoated cemented carbide was used.

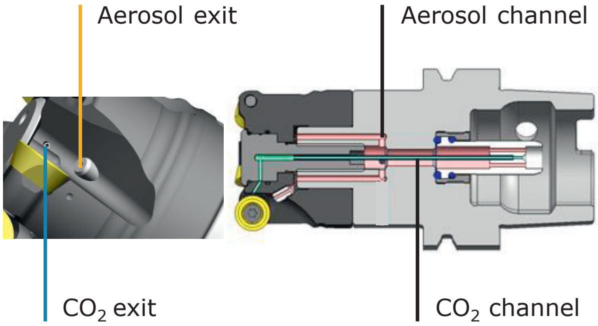

Fig. 3. Cryo·tec^{TM} tool cross section

4. Experimental set-up

To investigate the cryogenic milling with carbon dioxide, a 5-axis machining center LX 051 from the Starrag Group AG has been used. The machine was equipped with a 3-channel rotary feed through. The lance of the coolant supply system is spring loaded. With this set-up, two coolant media can be separated supplied through the machine tool spindle. The concept is based on one central channel for the cryogenic gas, CO_2 and one "Aerosol" channel for compressed air or MQL, equivalent to the tool concept.

4.1. Workpiece material

The high temperature high strength stainless steel 1.4962 (X12CrNiWTiB16-13) is a common used material in turbine industries. The alloy is used for turbine discs in large industrial gas turbines. This steel is also used in the aerospace, e.g. turbine discs, shafts, diffuser cases etc. The chemical composition is shown in table 2. The tensile strength is R_m = 730 $N{\cdot}mm^{-2}$.

Table 2. Chemical composition: Stainless steel 1.4962

C	Cr	Ni	W	Mo
0.07	15.50	12.50	2.50	0.80
0.15	17.50	14.50	3.00	1.20

4.2. Milling strategy

As demonstrator part a steam turbine blade was chosen. As machining strategy the radial multiaxial turn milling strategy (also known as helirough) was applied. The machining method was aligned to a three-staged turbine blade roughing process (Fig. 4):

- Roughing of the shroud (one entry)
- Airfoil roughing (four entries)
- Roughing of the root (two entries)

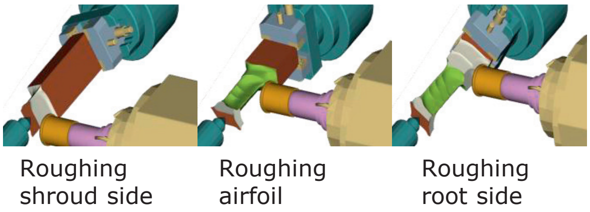

Fig. 4. Milling strategy (Source: IfP Zwickau)

In the first step, the cutting parameters were kept constant for both dry and cryogenic machining. To investigate the influence of the feed rate and the cutting speed, in a second step, both cutting parameters were increased for the cryogenic machining tests, Table 3. The milling tests for the measurements were carried twice.

Table 3. Cutting parameters

Coolant strategy	Cutting speed v_c	Width of cut a_e	Depth of cut a_p	Feed per tooth f_z
	$m \cdot min^{-1}$	mm	mm	mm
Dry machining	320	30 – 50	max. 3.0	0.4
CO_2 + Air	320	30 – 50	max. 3.0	0.4
CO_2 + Air	400	30 – 50	max. 3.0	0.55

4.3. Lubricoolant supply

Two coolant strategies were applied:

- Coolant strategy 1: dry machining strategy
- Coolant strategy 2: CO_2 + Air cooling

For internal supply of the lubricoolants, the aerosol dry lubrication device AEROSOL MASTER 4000cryolub® from Rother Technologie GmbH was used. The volume flow of the carbon dioxide CO_2 was kept as constant at a level of 10 kg/h (approx. costs of 1 USD/kg).

5. Experimental Results

In milling tests of the high temperature high strength stainless steel 1.4962 (X12CrNiWTiB16-13) the wear behavior of cemented carbide tools, the cutting tool and chip temperature and chip formation was compared under dry machining and under cryogenic cooling.

5.1. Tool wear behavior and cutting performance

The tool life behavior was investigated and assessed by measuring the flank wear with an optical microscope, Fig. 5. In the case of applying the same cutting parameters in the process, the flank wear VB could significantly be reduced by use of cryogenic cooling. After machining one blade, the flank wear could be reduced from 0.16 mm (dry machining) to 0.06 mm (cryogenic machining).

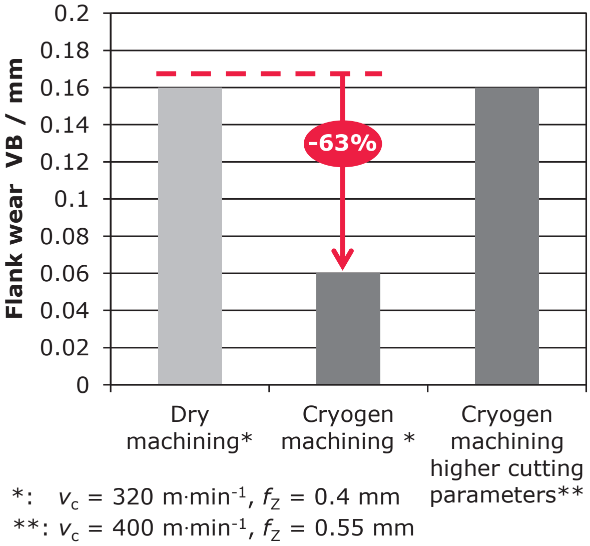

Fig. 5. Effect of cooling strategy on flank wear

In the second step, the cutting parameters cutting speed v_c and the feed rate f were increased with the aim to not negatively affect wear rate in comparison to dry machining. By use of carbon dioxide, the material removal rate could be increased going by 72% from $Q_w = 61\ cm^3 \cdot min^{-1}$ to $Q_w = 105\ cm^3 \cdot min^{-1}$ by maintaining the same level of flank wear in comparison to dry machining, Fig. 6.

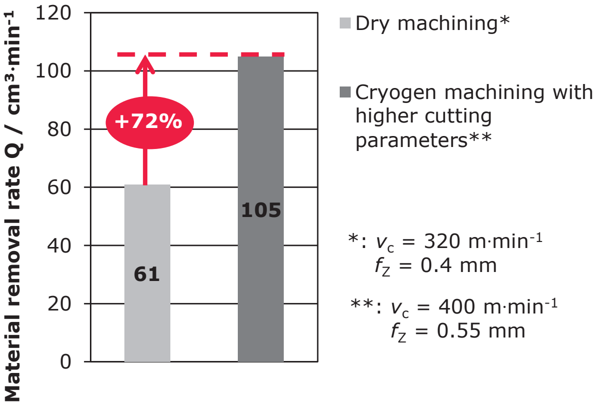

Fig. 6. Effect of cryogenic cooling on material removal rate

5.2. Process temperatures

The process temperatures were measured with an infrared digital thermometer after machining one dummy blade. The temperature of spindle, workpiece, tool body and cutting edge was measured. The temperature of the spindle is not effect by the cryogenic cooling. The tool temperature is highly affected by the CO_2 cryogenic cooling in comparison to machining with MQL, Fig. 7. The cutting edge temperature could be reduced from $T_{\text{cutting edge}} = 180$ °C to 80 °C, that means a reduction of -55%. Even the tool body temperature could be reduced by 43% from $T_{\text{tool}} = 70$ °C to 40 °C.

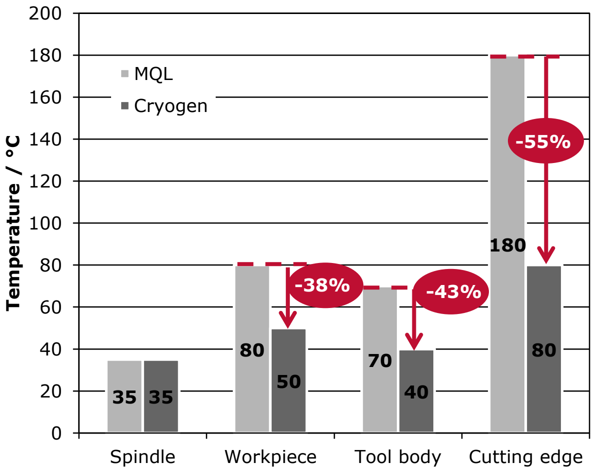

Fig. 7. Spindle, workpiece, tool and cutting edge temperatures

The same trend can be seen in the chip formation. Chips from the dry machining show a blue colour in comparison to the chips from the cryogen machining, where the colour of the chip material is golden, Fig. 8.

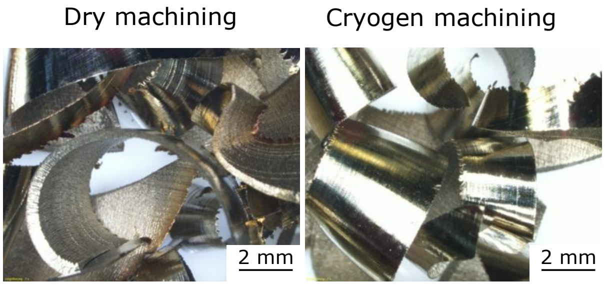

Fig. 8. Chips from dry machining and cryogenic machining

5.3. Workpiece surface quality

The machined workpiece surface quality was optically compared, Fig. 9. As wear rate is much lower when applying the cryogen cooling, the cutting edge remains sharper for a longer time of cutting. Sharper cutting edges lead to better surface qualities. On the other hand, cutting temperatures are much lower. The compensation of the heat generated in the material deformation and in friction processes can supress chemical processes and the adhesion mechanisms.

The workpiece surface from the dry machining process shows big adhesions. The cryogenic machined surface shows only very small adhered particles.

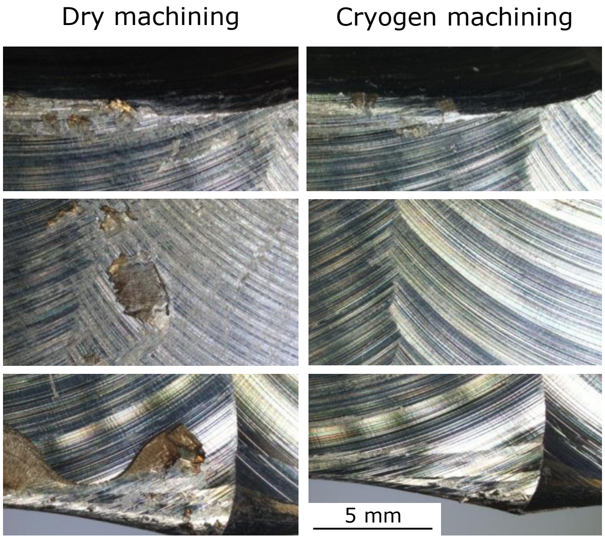

Fig. 9. Workpiece surface quality

6. Conclusion

The aim of the works was the development of cryogenic milling tools for cryogenic machining with an internal supply of liquid carbon dioxide directly into the cutting zone. The tools were developed in close work with a machine tool and rotary feed through manufacturer.

Studies of the effects of the cryogenic cooling on the tool wear rate, the spindle, workpiece, tool body and cutting edge temperatures, the chip formation as well as the surface quality in comparison to dry and MQL machining were done. Major effects of the cryogenic cooling can been seen in higher material removal rates (+72%) and in significant tool wear rate reduction (-63%). It was possible to reduce the process temperatures, e.g. the cutting edge temperature from 180° C to 80 °C. In addition, the use of carbon dioxide as cryogenic medium leads to better surface quality as the adhesion of particles the chips could highly be suppressed.

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