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Sub-zero cooling: A novel strategy for high performance cutting

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A R T I C L E I N F O

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A B S T R A C T

In this paper, a novel cooling strategy for high performance cutting is presented. A metalworking fluid, composed of water and polyhydric alcohols is applied at temperatures below 0 °C, but above the temperatures used for cryogenic cutting. This cooling strategy is applied when rough turning Ti-6Al-4V. An analysis of temperatures, forces, tool wear and chip formation is carried out. The results are compared with those obtained using emulsion, CO_2, LN_2, and dry turning. It can be shown that when tempering the sub-zero metalworking fluid down to −30° C, tool temperatures as well as tool wear are reduced, and favourable chips are produced.

1. High performance cutting of Ti6Al4V

Ti-6Al-4V is characterized by high strength, low thermal conductivity as well as a high chemical reactivity. Due to these properties, the machining of titanium alloys is associated with high mechanical, thermal and chemical loads of the tool. The main wear mechanism is adhesion-dissolution diffusion of the cobalt matrix of cemented carbide tools [1]. Crater wear [2] is the primary wear form at cutting speeds <80 m/min, leading to an unstable cutting edge [3]. The development of high performance cutting (HPC) of titanium aims at lowering the temperature of the tool-workpiece and tool-chip interface [3]. Common methods are coatings [4], small cutting edge radii [5] (requiring frequent tool changes), and the improvement of cooling strategies.

Liquid nitrogen (LN_2) and carbon dioxide snow (CO_2) are applied with the aim of achieving a maximum cooling effect [6]. Due to temperature differences far above the Leidenfrost point, LN_2 tends to film-boiling [7]. Then, a gaseous boundary layer is formed, which reduces heat transfer [8]. This can be compensated by increased supply-pressures [9], however accompanied by a higher consumption of LN_2. CO_2 is supplied as a solid-gaseous two-phase mixture. In this state of aggregation, a poor heat transfer is achieved. As a result, while its application is good for finishing, the temperature in the tool–chip and tool–workpiece interface is insufficiently lowered at high depths of cut [10].

The thermo-mechanical impact of cutting on the tool can also be lowered by reducing the tool–chip contact length and hence the adhesion–dissolution–diffusion [11]. This can easily be achieved via a jet of liquid metalworking fluid (MWF), directed in the tool–chip interface at high velocities. This results in a smaller radius of the chip curvature [12], as the jet forms the chip, lower wear and in favourable chips [13]. The use of an MWF-jet is more cost-effective, provides better process reliability and is easier to use than cryogenic coolant [14].

The aim of our research is to combine the advantages of both cryogenic cooling and liquid MWF in machining of Ti-6Al-4V. Therefore, a novel sub-zero MWF is applied and compared to other cooling strategies with regard to forces, tool wear and chip formation.

2. Novel sub-zero cooling approach for HPC

The sub-zero MWF examined in our research is a mixture of water and the polyhydric alcohol ethane-1,2-diol, also known as ethylene glycol. Depending on its composition, a freezing-point depression down to −49 °C is possible, maintaining its stable liquid state [15], Fig. 1. Furthermore, this novel sub-zero MWF is additized with corrosion inhibitors and, to improve wetting behavior, with organophosphates.

The application of a sub-zero MWF allows to combine the advantages of cryogenic machining and high-pressure-jet-cooling [17]:

- Liquid state, sub-zero temperature, high specific heat-capacity, high heat conductivity, good heat transfer.

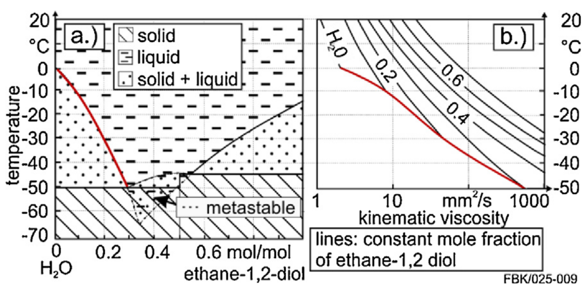

Fig. 1. Phase diagram (a) and kinematic viscosity at ambient pressure (b) of sub-zero MWF mixtures containing water and ethane-1,2-diol, adapted from Refs. [15,16].

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- Good lubrication properties, good wetting.
- Additives usable.
- High mass flows and nozzle exit velocities.
- Closed loop operation of MWF.

The viscosity of this sub-zero MWF is strongly temperature-dependent (Fig. 1). The higher the viscosity of a MWF, the lower is the heat transfer. Therefore, in this work, the sub-zero MWF (0.33 mol ethane-1.2-diol/1 mol sub-zero MWF) is examined at −30 °C, which is above the minimal operation temperature of −49 °C (Fig. 1).

3. Experimental setup

External cylindrical turning via a CNC lathe was applied to machine the workpieces. The workpieces with a diameter of 50 mm and a length of 130 mm were clamped between centers. ($\alpha + \beta$) titanium alloy Ti-6Al-4V with a hardness of 315 HV 10 of one batch was machined. The cuttings tools were uncoated indexable insert (cemented carbide, K313, Co 5%, WC 95%). No chip breaker was used to allow for precise wear measurements according to ISO 3685 [18]. To favor chip breakage, a negative rake angle of $\lambda = -6°$ was set. All workpieces were prepared by finishing cuts down to a diameter of 49.5 mm (±0.01) under dry conditions.

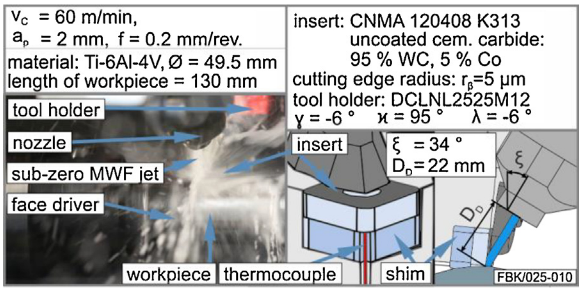

Fig. 2. Experimental setup.

Cutting conditions were used which reduce the specific thermo-chemical load, see Fig. 2: high depths of cut, low feed rates, low cutting speeds [9] and small cutting edge radii [5]. Those parameters are comparable to standardized processes [9]. Six different cooling strategies were examined: dry condition, LN_2 and CO_2–snow cooling, ester (8%) based conventional MWF (MWFc), and sub-zero MWF at −30 °C (MWF-30) as well as at 20 °C (MWF + 20). The parameters of the cooling conditions are listed in Table 1.

Table 1
Parameters of applied cooling strategy.

	Dry	LN_2	CO_2	MWFc	MWF − 30	MWF + 20
Temperature of MWF in °C	–	−196	−78.5	20	−30	20
Mass flow in kg/min	–	1.1	1.75	11.1	11.1	11.1
Pressure of MWF supply in bar	–	2	≈60	12	12	12
c_{pm} in J/g*K	–	–	–	4.1	3.3	3.3

For the dry condition, the interior of the machine was flooded with CO_2 to achieve an inert atmosphere as titanium oxidizes exothermically during machining, which can cause chip fires and titanium-dust explosions [19].

The same nozzle positioning was applied for all cooling strategies, see Fig. 2. The nozzle diameter was varied for the conventional and the sub-zero MWF to ensure the same nozzle exit velocity of 27.1 m/s.

Due to the constant feed travel, the cutting time of subsequent cuts on one workpiece changes as a function of the workpiece diameter as follows: 93 s (1st cut), 85 s (2nd cut), 76 s (3rd cut), 69 s (4th cut) and 60 s (5th cut). For the evaluation of temperature and forces (cutting force, passive force, feed force), the mean value was calculated for the first 55 s of each cut. Thereby, it was assured that the same duration of heat impact as well as duration of cooling is compared for different cuts. Uniform starting temperatures of 20 °C were ensured before each cut on the tool and workpiece and coolant was started 3 s before starting feeds and speeds. Tool wear evaluation was carried out using a structured-light 3D scanner and SEM. The wear parameters were all measured according to ISO 3685 [18]. All experiments were repeated twice.

4. Results and discussion

4.1. Temperature of tool

The tool temperatures as a function of the cutting time of the first cut are plotted in Fig. 3 for the different cooling strategies. In Fig. 3, 0 s marks the engagement of the tool into the workpiece. The coolant was activated 3 s before. As a consequence, the temperature of the insert dropped when applying coolants at a temperature below room temperature. It is noticeable that, for the period before tool engagement, LN_2 results into the lowest temperatures while CO_2 shows higher temperatures than the sub-zero MWF-30. That is, for this period, the very low temperature of LN_2 provides the best cooling effect, while the better heat conductivity and wettability of the sub-zero MWF results into lower temperatures at the tool than CO_2, despite 50 °C higher temperatures of the coolant itself.

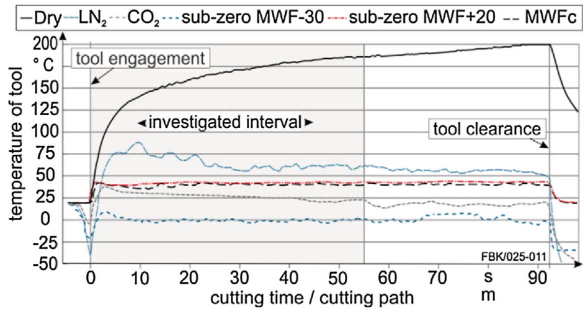

Fig. 3. Temperature of tool as a function of cutting time.

During the cut, dry condition results into constantly rising temperatures, reaching 200 °C after 90 s. All other strategies resulted into lower temperatures. The MWFc and the MWF + 20, each delivered at 20 °C, show quite similar temperature curves, the MWF + 20 resulting into slightly higher temperatures. This can be led back to the higher specific heat capacity and lower viscosity of the MWFc compared to the sub-zero MWF.

Most notably, the LN_2 strategy has the worst cooling effect (besides dry condition). This can be attributed to the Leidenfrost-effect [8]: due to the high temperature differences caused by machining, film-boiling of the LN_2 causes a very poor heat transfer. This obviously was not the case in the period before tool engagement, where the temperature difference between LN_2 and the tool was 160 °C. The temperature difference becomes smaller with time, as the heat input from the process reaches a steady state and the continuous supply of LN_2 results into cooling down the tool (despite film-boiling). This causes the observable

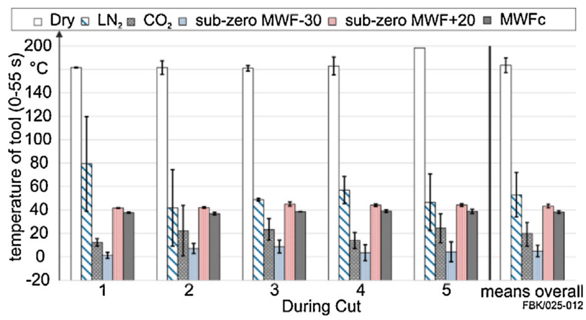

Fig. 4. Mean values of temperatures during cuts 1–5.

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