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Influence of coolant flow rate on tool life and wear development in cryogenic and wet milling of Ti-6Al-4V

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Abstract

The use of cryogenic coolants has emerged as a way to improve productivity in machining Ti-alloys. In this study, liquid carbon dioxide is used as coolant in face milling of Ti-6Al-4V with PVD coated inserts. The influence of coolant flow rate on tool life is studied by means of controlled experiments. Tool life is shown to improve with higher flow rates of coolant, the effect being stronger in cryogenic compared to wet milling due to the fact that the cryogenic coolant delays the wear development. The tool life is determined by notch wear irrespective of coolant nature in titanium milling. Different analyses were used to understand the mechanism behind the delay of notch wear development when using carbon dioxide coolant.

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Keywords: Cryogenic machining; Milling; Titanium; Wear; Carbon dioxide

1. Introduction

In recent years, the use of cryogenic coolants has emerged as a way to improve tool life, and thereby increase productivity, in the machining of difficult-to-machine materials. Different strategies exist in terms of the application of the coolant (e.g. precooling of the workpiece, cooling of tool back, cooling of tool rake and/or flank face) and the choice of coolant itself (e.g. liquid carbon dioxide, liquid nitrogen, compressed cold air) [1]. A variety of materials has been studied in cryogenic machining: steel [2], nickel alloys [3], titanium alloys [4], metal matrix composites [5]. Yet, most of the research has been focused on turning operations.

Titanium alloys like Ti-6Al-4V are used in many industrial sectors, with applications ranging from aero-engines to medical implants. They have a very high strength-to-weight ratio and toughness as well as the ability to retain their strength at high temperatures. In addition, they offer great resistance to corrosion. These excellent properties create challenges when machining titanium alloys. Further reducing their machinability is their low thermal conductivity, leading to localized high temperatures in the cutting zone, and their reactivity with most tool materials [6].

In an effort to improve the machinability of this material, cryogenic machining of titanium alloy Ti-6Al-4V has been widely studied. Most commonly, liquid nitrogen is used as a coolant. Improvements in terms of tool wear and life have been consistently reported compared to dry machining [4, 7] and when applying conventional cooling [8, 9]. For example, Su et al. [10] reported almost double tool life compared to that obtained when dry milling by application of compressed cold nitrogen gas at -10 °C. Combining minimum quantity lubrication (MQL) with cold air at -15 °C, -30 °C or -45 °C, Yuan et al. [11] found the evidence of wear reduction compared to dry, wet or MQL conditions. Depending on the coating of the tool and cutting speed Lee et al. [12] have also reported an increase in tool life of 44-55 % for liquid nitrogen cooling compared to that in dry milling.

According to the Joule-Thomson effect, liquid CO_2 expands to atmospheric pressure to form a mixture of CO_2 snow and

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gas. The temperature of the CO_2 snow is theoretically -79.05 °C and it can provide an efficient cooling effect [13]. There have been very few studies on the machining of titanium alloys using liquid CO_2 as a cryogenic coolant. Machai and Biermann [13] have performed experiments in turning of Ti-10V-2Fe-3Al with liquid carbon dioxide. They reported lower flank wear with CO_2 cooling than with conventional emulsion cooling. The development of notch wear is suppressed, both with uncoated and coated tool. Dilip Jerold [14] compared turning of Ti-6Al-4V with CO_2 cooling and emulsion cooling. With a PVD coated tool, he reported a reduction of crater wear and flank wear of approximately 60 % using CO_2. Klocke et al. [15] showed similar reduction in flank wear for uncoated tools. However, little is known about cryogenic milling of Ti-6Al-4V using carbon dioxide as a coolant. The aim of this study is to examine the tool life and wear development under this cooling condition compared to conventional emulsion cooling. In particular, the influence of the coolant flow rate is analyzed.

2. Experimental work

The machining experiments presented in this study consist of face milling under different cooling conditions.

The workpiece material is the α/β titanium alloy Ti-6Al-4V in forged and annealed condition. All milling tests were conducted on a Hermle C40U Dynamic machining centre. A cutter (CoroMill 600-040Q16-12H) equipped with two PVD coated inserts (600-1252E-ML 1030) were used. Each insert had an arc of engagement of 180°. All experiments were carried out using the same cutting data: cutting speed v_c = 80 m/min, feed per tooth f_z = 0.15 mm/tooth, depth of cut a_p = 2 mm and width of cut a_e = 30 mm. The cutting data has been chosen according to Sandvik Coromant recommendations.

The cooling conditions used were either conventional flood emulsion (Blasocut BC 25) or cooling with liquid carbon dioxide (CO_2) with different flow rates. In both cases, the supply pressure was constant at 50 bar. The standard cutter was redesigned for CO_2 cooling to obtain an appropriate distance between the nozzle outlet and the cutting edge. Various flow rates were then achieved using three different nozzle diameters as shown in Table 1. A photograph of the tool used with cryogenic cooling is shown in Fig. 1. The same nozzles were used for emulsion cooling.

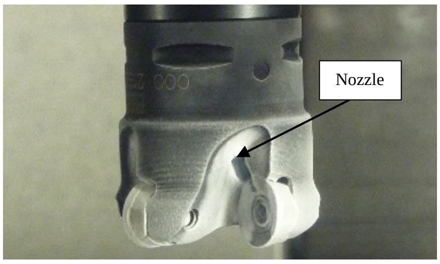

Fig. 1. Tool used with cryogenic cooling

Table 1. The different flow rates of CO_2 for cryogenic cooling.

Coolant	Nozzle (diameter)	Flow rate [kg/min]
CO_2	A (Large)	0.65
CO_2	B (Medium)	0.19
CO_2	C (Small)	0.15

Tool life was evaluated by measuring flank wear and notch wear. The tool life criteria were set to VB = 0.3 mm for flank wear and VB_N = 0.4 mm for notch wear. Tool wear measurements were done under optical microscope (Nikon SMZ1000) equipped with special software for tool wear measurement. The inserts were additionally examined by a Zeiss SUPRA 40 Scanning Electron Microscope to determine the dominant wear mechanism.

3. Results

In order to fully understand how the nature of the coolant can improve the tool life performance, it is essential to study the tool wear development. The examination of the inserts used for machining under wet condition at different cutting times reveals the different stages of wear development (see Fig. 2). At the initial stage, after 3 minutes of cutting time (Fig. 2-a,d,g), the wear development on the cutting edge is very low.

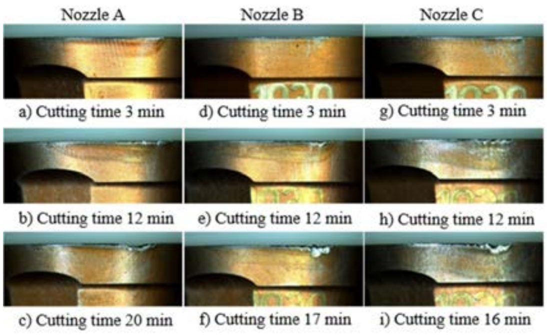

Fig. 2. Optical microscope images of wear development in wet milling

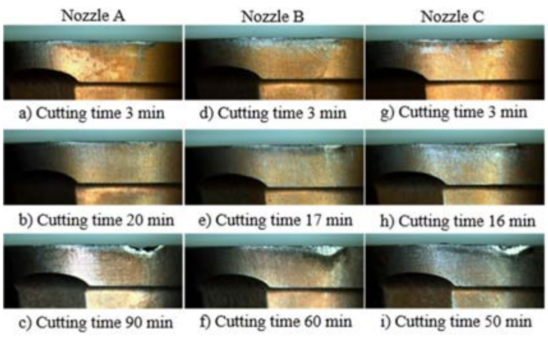

Fig. 3. Optical microscope images of wear development in cryogenic milling

At the intermediate stage, after 12 minutes of cutting time, (Fig. 2-b,e,h), the cutting edges display, in addition to growing flank wear, different wear types such as partial destruction of the cutting edge and notch wear. As the machining process continues, the notch wear appears to be the dominant wear mode and limits the tool life.

Fig. 3 indicates the state of the cutting edge at different time intervals when utilizing cryogenic cooling. As evident, in the first stage after three minutes of cutting time, the wear progression rates are nearly similar to those of wet condition, whereas the notch wear development and edge destruction of the cutting edge are delayed to significantly longer machining times. As it can also be seen in Fig. 2 and Fig. 3, the flow rate of the coolant has an influence on the tool life both in the case of standard emulsion and with cryogenic cooling. Higher flow rate leads to longer tool life. However, the influence of the flow rate is stronger when using carbon dioxide as a coolant. The increase in tool life between the lowest and the highest flow rate is 25 % when using the emulsion and 80 % when using CO_2. In addition, the results clearly indicate that the use of cryogenic coolant greatly improves the tool performance compared to emulsion with increases in tool life of up to 200 % or more.

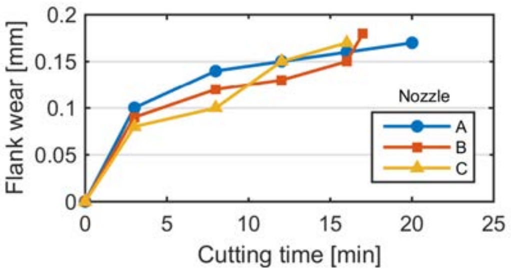

Fig. 4. Flank wear development as a function of the cutting time with emulsion cooling.

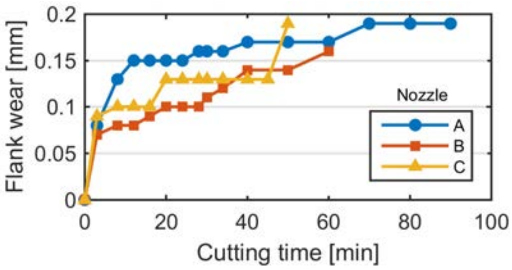

Fig. 5. Flank wear development as a function of the cutting time with cryogenic cooling.

The development of flank wear for milling with emulsion and cryogenic cooling is shown in Fig. 4 and Fig. 5. The tool life criterion for flank wear (VB = 0.3 mm) is not met in any of the experiments, thereby the flank wear is found to have a minor influence on tool life irrespective of the nature of the coolant. The development of flank wear is slower and more predictable with cryogenic cooling compared to emulsion cooling. In the wet condition, a flank wear of 0.17 mm is reached after 20 minutes for nozzle A. Introducing the carbon dioxide as the coolant, it takes 40 minutes to reach the same level of flank wear. In both cooling conditions, however, the flow rate of the coolant seems to have little influence on the rate of development of flank wear.

The development of notch wear for conventional and cryogenic cooling is shown in Fig. 6 and Fig. 7. It is clearly seen that irrespective the nature of the coolant, notch wear is the determining factor for tool life evaluation in milling of titanium. Evidently, the use of carbon dioxide as a coolant delays the development of notch wear and extends the tool life. A clear influence of the flow rate of carbon dioxide can also be observed. The earliest measurement of notch wear in the case of the lowest flow rate of CO_2 was made at 34 minutes. Interpolation of the data (Fig. 7) indicates that the same level of notch wear is reached after 45 minutes for nozzle B and 74 minutes for nozzle A. Fig. 8 shows the tool life obtained for both cooling conditions and the three different nozzles.

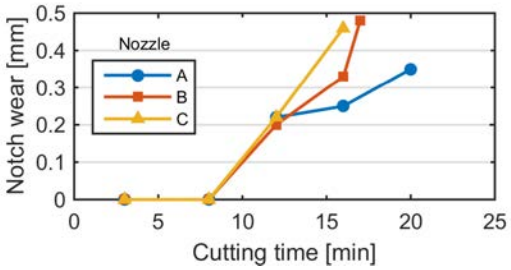

Fig. 6. Notch wear development as a function of the cutting time with emulsion cooling.

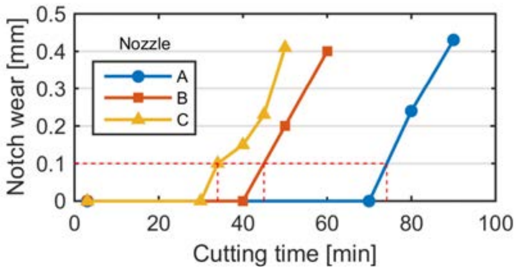

Fig. 7. Notch wear development as a function of the cutting time with cryogenic cooling.

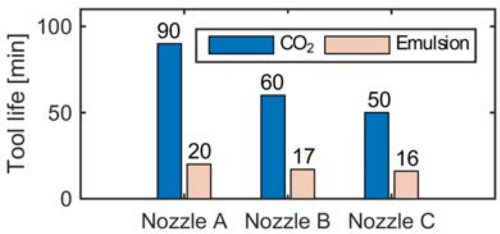

Fig. 8. Tool life in face milling of Ti-6Al-4V with cryogenic and emulsion cooling.

4. Discussion

The results presented in Fig. 2 and Fig. 3 clearly indicate that the tool performance is mainly determined by notch wear under both cooling conditions. A detailed analysis of the worn inserts by SEM reveals differences in wear development on the cutting edge between cryogenic and wet conditions. Fig. 9 shows the part of the cutting edge where the notch is located. As evident, thermal cracking is present both for CO_2 and emulsion cooling conditions. However, cracks have propagated in different directions when emulsion cooling is adopted, leading to earlier chipping of the cutting edge compared to CO_2 cooling. In the latter case, the cracks have not propagated laterally.

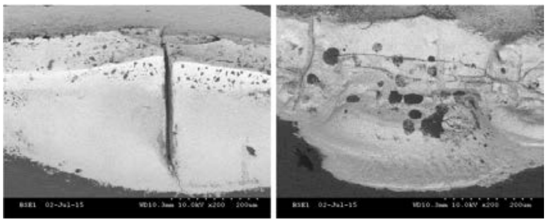

Fig. 9. SEM image of worn inserts. CO_2 cooling after 60 min (left) and emulsion cooling after 17 min (right). Nozzle B was used in both cases.

It is well documented that the cyclic nature of milling operation demands tools that can resist to repeated impact loads and are stable under alternating temperatures [16]. Particularly, the latter is of great importance when machining titanium alloys. The cutting temperatures, when machining titanium alloys, are significantly high and can exceed 1000 °C [6]. The large temperature fluctuations during the cutting and non-cutting periods can induce large cyclic thermal stresses on the cutting edge and promote the initiation of thermal fatigue cracks [17]. Once these cracks have initiated, they normally grow perpendicular to the cutting edge as the process continues and eventually lead to chipping and/or flaking. The positive influence of the CO_2 flow rate on the tool life can therefore be associated to its contribution on heat dissipation from the cutting zone during the process. The CO_2 provides a uniform cooling over the contact area between the chip and the tool. An increasing flow rate of CO_2 gives a lower temperature on the cutting edge, leading to longer tool life. However, Klocke et al. [18] have argued that the cutting temperature is not the only reason for the reduced wear with CO_2 cooling. The temperature measurements by the authors when turning stainless steel (X5CrNi18-10) and Ti-6Al-4V under both conventional emulsion and CO_2 cooling conditions indicated only a slight difference between the cutting temperatures at similar cutting conditions. The suppression of oxygen by CO_2 gas at the cutting zone was believed as a possible explanation. Further investigation on this matter is needed.

5. Conclusions

From the study of Ti-6Al-4V milling with CO_2 coolant vs. conventional emulsion, the following conclusions can be obtained:

- Tool life is not determined by flank wear in either cooling condition (CO_2 or emulsion).
- The flow rate of coolant has limited influence on the rate of flank wear development.
- The main type of wear determining tool life is notch wear, irrespective of the nature of the coolant.
- Cryogenic cooling with CO_2 reduces the tendency of thermal cracks to propagate laterally, delaying the chipping of the cutting edge.

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