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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.

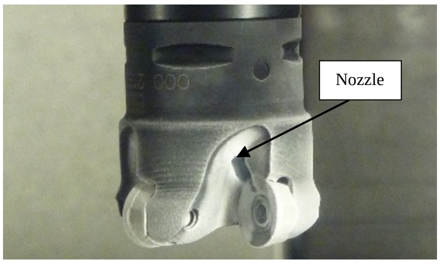

Fig. 1. Tool used with cryogenic cooling

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.

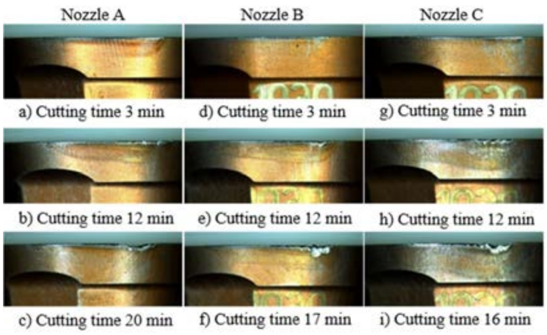

Fig. 2. Optical microscope images of wear development in wet milling

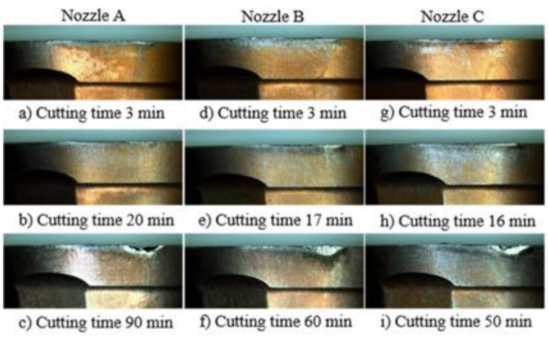

Fig. 3. Optical microscope images of wear development in cryogenic milling

At the intermediate stage, after 12 minutes of cutting time, (Fig. 2-b,e,h), the cutting edges display, in addition to growing