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Influence of cryogenic cooling on tool wear and chip formation in turning of titanium alloy

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Abstract

Machining of high performance materials such as titanium alloy keeps growing especially in the aerospace and medical industries. Due to the low thermal conductivity property of titanium material, there is thermal-related challenge which causes poor machinability and productivity. In this paper, influence of cryogenic cooling on tool wear and chip formation was investigated for turning titanium alloy at high speed cuttings. The results showed that tool wear resistance increases when using the developed cryogenic modular compared to oil-based coolant. In addition, a study on chip morphology showed different chip formations and thicker secondary deformation zone when machining under oil-based coolant condition compared to cryogenic condition.

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Keywords: Cryogenic machining; Titanium alloy; Tool wear; Chip formation

1. Introduction

Heat generation and thermal conductivity significantly influence machinability and productivity of machining processes, especially for cutting difficult-to-cut materials such as titanium-based alloys, nickel-based alloys, stainless steel and hardened steels. Machinability of titanium alloy is poor due to its low thermal conductivity which limits the rate of heat dissipation during cutting by the chips.

To enhance the machinability, cutting fluid is used to reduce tool wear progression. However, implementation of oil-based coolant has been reported as inefficient due to its poor accessibility to very small areas. Moreover, it has low capability to cutting temperature reduction and is not environmentally friendly.

Cryogenic machining is the process of implementing and delivering non-oil-based cooling media such as liquid nitrogen (LN_2) and carbon dioxide (CO_2) to the cutting zone. It is gaining popularity due to its ability to cutting temperature reduction and is a clean process [1, 2]. At atmosphere pressure, the boiling temperatures of LN_2 and CO_2 are -196˚C and -78˚C respectively. The benefits of using LN_2 as compared to metal working fluids (MWFs) e.g. oil-based coolant (as commonly use in industry) are its clean, colorless, odorless, tasteless, non-toxic, non-combustible and non-corrosive characteristics. When LN_2 is applied into the cutting zone, it will evaporate and return back to the atmosphere, leaving no residue and contamination on cutting tool, workpiece, chip and machining area. Therefore, there is no need of coolant disposal and post-process of cleaning due to contamination and the process is environmentally friendly compared to conventional cooling fluids.

Machining difficult-to-cut materials under cryogenic environment were investigated and the results showed improvement in machinability for Inconel 718 [3-5], Titanium based alloy [2, 6, 7] and stainless steel [8]. The existing practice in machining shop floors is still using flood coolant and/or high pressure flood coolant. They include cutting fluids in the forms of oil, oil-based or water-based emulsion. In functional aspect, these methods are not considered efficient

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for coolant accessibility, cutting temperature reduction and lead to shorter tool life for difficult-to-cut materials.

More importantly, in ecological aspect, these cutting fluids have high human (machine operators) toxicity and are not environmentally friendly due to the chemicals in the coolants. Direct contact with cutting fluids can causes occupational skin diseases while inhalation of oil/mist vapors can trigger allergic respiratory diseases. Furthermore, the quality of cutting fluid deteriorates with accumulated usage in machining applications. These cutting fluids require regular maintenance as they provide rich environment for bacteria and fungi growth. In short, these cutting fluids need proper management in term of handling, transportation, treatment and disposal.

Cryogenic machining is one of the more environmentally conscious technologies [9]. The technology has been studied in laboratory for the past decades. However, one challenge is how to implement this technology to machine shop floor. It is highly difficult to integrate cryogenic media with existing machine tool due to the negative boiling points of LN_2 that could instantly freeze the machining system. This is due to the limitation in equipment and know-how to integrate or retrofit into existing commercial cutting tool holder. The widely used existing practice is mainly to exploit nozzle/hose based delivery. These nozzle setups are not attached to the cutting tools and are difficult to adjust especially when the nozzle is cold. Hence the mentioned issues limit the implementation cryogenic machining and the full advantage of using it is not taken off.

The aim of this paper is to investigate the effects of using liquid nitrogen cooling through a modular system on tool wear and the chip formation for turning of Ti6Al4V at high speed cuttings, while comparing with conventional machining using oil-based coolant.

2. Experimental details

2.1. Machine tool and cryogenic modular system

Turning experiments were carried out on Mazak T6 quick CNC lathe equipped with oil based coolant and supplied with flow rate of 20 l/min with pressure of 6 bars for flood coolant machining condition. An additional customized cryogenic modular system was integrated to lathe machine for cryogenic condition in Fig. 1.

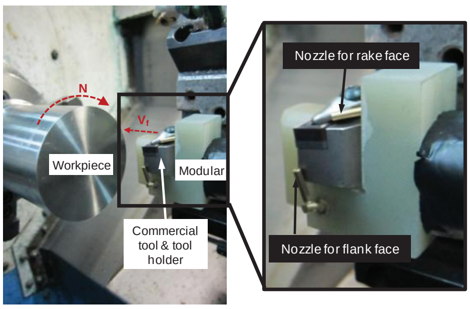

Fig. 1.Cryogenic module attached to the tool holder for turning process on Mazak turning centre

The cryogenic modular system is a customized design to deliver LN_2 to the machining process. It can be attached and detached from commercial tool holder, with two major cryogenic media delivery channels to the rake and flank faces of the cutting tools. The nozzles will directly deliver cryogenic media to both cutting tool faces. The angle of the delivery can be further fine-tuned by using the flexible pivot nozzle function. The module is insulated and hence it is able to maintain liquid nitrogen at liquid phase and deliver it at a steady flow rate. The flow rate for cryogenic media was controlled and regulated at 0.35 l/min while pressure was set at 4 bars.

2.2. Workpiece material, cutting tools and cutting conditions

The material selected for this study was cylindrical shape Ti-6Al-4V bars with original diameter of 60 mm. Coated carbide inserts, CNMG120412, supplied by Mitsubishi were selected as the cutting tools. The turning experiments were done under both flood coolant and cryogenic machining environments. Detailed cutting conditions are summarized in Table 1. The criterion for terminating the turning tests was when one of the tools reached a flank wear of 200 μm or a significant chipping.

Table 1. Cutting conditions.

Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)
70 and 100	0.25	0.5

2.3. Tool wear and chip analysis

Machinability of Titanium alloy and coolant effects were analyzed in terms of tool wear and chip morphology. Cutting tools were withdrawn after every two passes of turning. Both flank and rake wears were analyzed. Flank wear and tool-chip contact length were observed and measured using high depth field optical microscope. Tool-chip contact length on rake face (in Fig. 2) represents the length of seizure and frictional interface between chip formation and rake face which generates along the secondary deformation zone.

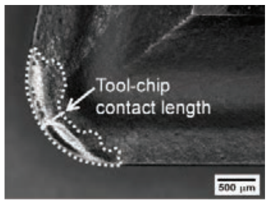

Fig. 2. Tool chip contact length on the rake face

Chips were collected, mounted and etched for morphology analysis using optical microscope. In addition, radius of chip curvature was measured.

3. Results and discussions

3.1. Tool wear

Tool wears were evaluated and their progressions were measured. Tool wear mechanisms found on inserts were of