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The influence of cryogenic cooling on milling stability

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ABSTRACT

Cryogenic cooling is emerging as an effective process for high performance machining. However, the influence of cryogenic cooling on milling stability is seldom reported. This paper involves experimental study on the effect of cryogenic cooling on milling stability, using a dedicated cryogenic cooling system to applying liquid nitrogen (LN2) jet to the cutting zone. We observe that cryogenic cooling leads to higher stability limit compared with conventional milling operations, which indicates that the cutting efficiency can be improved greatly in LN2 environment as opposed to the conventional one. The stability improvement is explained from the perspective of machining dynamics parameters variation between the two conditions. Cutting force coefficients and modal parameters of spindle-tool system are identified during cryogenic machining, then milling stability lobe diagrams are predicted by time domain and frequency domain methods. On the basis of milling stability analysis, the enhancement of stability boundary is attributed to the significant reduction of cutting force coefficients during cryogenic cooling. Additionally, the experiment result indicates that cryogenic cooling decreases the dominant modal frequency of the spindle-tool system, which shifts the milling stability boundary slightly to lower spindle speed range. The explanations are verified by a plenty of cutting tests.

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1. Introduction

Cooling plays a significant role in metal cutting process for its main functions in transferring excessive heat and reducing tool wear. Increased application of difficult-to-machine materials, such as nickel based high-temperature alloy, titanium alloy in aerospace and energy industry promotes the development of new cooling methods to get higher machining performance, better surface integrity economically and environmental-friendly. In the past decades, various methods have been proposed, including high-pressure coolant (HPC), minimum quantity lubrication (MQL), compressed air cooling, and cryogenic cooling etc., which has been summarized in detail by Sharma et al. (2009). As one of these methods, cryogenic cooling is emerging as a promising approach for application in industry and LN2 is the most widely used cryogenic coolant for its non-toxic and sufficient resource (Yildiz and Nalbant, 2008). Much research has been done to explore and confirm the improvement of cryogenic cooling on machinability. Hong et al. (2001b) proposed an economical approach to transfer LN2 to flank and rake face near the cutting edge and five times enhancement of tool life was achieved when turning Ti6Al4V at cutting speed of 150 m/min. Moreover, they found that LN2 can act as an effective lubricant (Hong et al., 2001a), which was validated by the reduction of feed force and thickness of secondary deformation zone. Wang and Rajurkar (2000) investigated the cryogenic machining of hard-to-cut materials, and their result showed that cryogenic cooling can enhance tool life and surface roughness significantly but has no remarkable influence on the cutting force. Venugopal et al. (2007) investigated the tool wear in cryogenic turning of Ti6Al4V alloy and found that cryogenic cooling enhances tool life substantially at moderate cutting speed of 70 m/min. Khan and Ahmed (2008) found that the tool life increases more than four times when machining AISI304 stainless steel with modified tool, in which the insert is cooled by LN2 through an internal chamber. While most of publications about cryogenic cooling focused on turning operation and its influence on machinability, there is almost no report about the stability in cryogenic milling.

Pušavec et al. (2011) conducted an experimental study on the influence of cryogenic cooling on process stability in turning operations, in which coarse-grained entropy rate (CER) method was used for detection of chatter in cutting tests. It is observed that a higher machining stability limit is achieved during cryogenic machining due to the reduction of specific cutting force components. In fact, Chatter in milling operation is always gaining significant attention in order to achieve higher productivity and better surface finish, which is very important in high speed machining (HSM) of aluminum alloy and low speed milling of thermal resistant alloy. With cryogenic cooling being applied to aerospace industry, where

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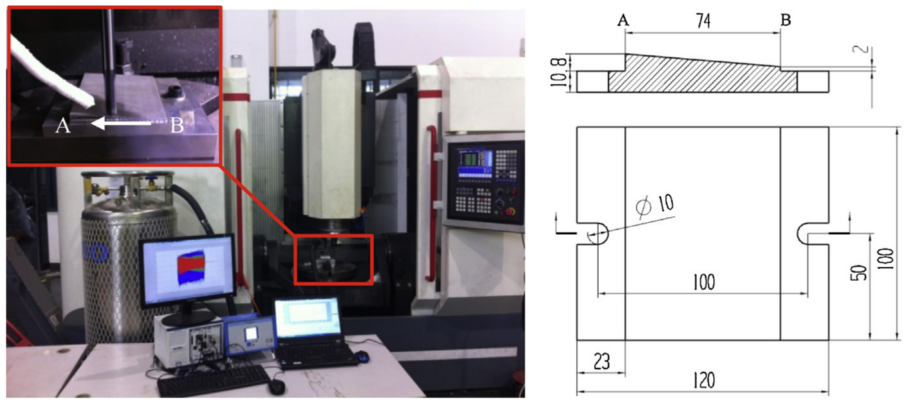

Fig. 1. Experiment setup for end milling with varying cutting depth and cryogenic cooling system.

Table 1
Tool parameters.

Tool	Diameter (mm)	Flutes num	Helix angle (deg)	Overhang (mm)	Material
Short cutter	8	2	30	40	Carbide
Long cutter	8	2	30	64	Carbide

Table 2
Cutting parameters for end milling with varying axial depth.

Tool	Spindle speed (rpm)	Axial depth (mm)	Radial depth (mm)	Feed rate (mm/tooth)
Short cutter	12,240	2–8	4	0.05
Long cutter	12,240	2–8	1.2	0.05

milling occupied most of material removal process, it is necessary to analyze its influence on milling stability so as to optimize the process.

The remainder of this paper offers the followings:

- We report the experiments of great milling stability limit improvement under LN2 condition. End milling tests with varying axial depth are carried out to show the difference of stability limit under dry and cryogenic conditions. In order to explain the difference, cutting force coefficients and modal parameters of a two-degree-of-freedom (2-DOF) end milling system are identified before and after cryogenic cooling. The SLDs are predicted using time domain and frequency domain methods.
- To confirm the stability limit differences shown in predicted SLDs, a series of experiments are conducted to catch the variation of stability boundary after cryogenic cooling.

2. Experimental conditions and procedure

The experiments are performed on a machining center VMC-50 with maximum spindle speed 14,000 rpm. In the first experiment, to achieve continuously varying axial depth, a specific workpiece made of 7075-T6 aluminum alloy is prepared (Fig. 1). There is a slope on the workpiece and axial depth a_p varies from 2 mm (side B) to 8 mm (side A) linearly after machining a path of 74 mm long. In the case of cryogenic milling, a copper nozzle is mounted on a fixture moving along with the spindle housing, through which LN2 jet is sprayed into cutting zone. Both short stiffer cutter and long slender cutter are adopted in order to reveal the influence of cryogenic cooling on the onset of chatter as well as the vibration during post-chatter stage. The tool parameters are listed in Table 1.

Cutting forces are measured by a Kistler9257B multicomponent dynamometer mounted on worktable and are recorded by a Labview-based PC data acquisition system. The cutting parameters are listed in Table 2, and sampling rate is set as 40 kHz so that the dynamic cutting force can be measured precisely during high speed ($s > 10{,}000$ rpm).

In the case for experimental verification of SLDs, end milling tests with constant axial depth are performed using the long slender end mill mentioned in Table 1 ($L/D = 8$), which is mounted in a HSK-A63 tool holder by collet chuck. As reported in several studies on milling dynamics, cylindrical end mill with large length-diameter ratio is prone to have a single dominant vibration mode, which will make it more convenient for the following milling stability analysis (Gradišek et al., 2005). The workpiece is a 7075-T6 aluminum alloy block fixed on dynamometer, which can be regarded as rigid for its much higher stiffness.

A number of cutting tests are conducted to catch the variation of SLD for half-immersion down-milling under cryogenic cooling, in which a straight path about 80 mm long is machined repeatedly at different points in the cutting parameter space of spindle speed and axial depth. The feed rate is set as $f_t = 0.05$ mm/tooth.

In order to detect the occurrence of chatter during milling process, cutting forces and sound pressure signals are recorded simultaneously by Kister9257B dynamometer and B&K 4189 free-field microphone at sampling rate 40 kHz. A small label is pasted on the tool holder and periodic 1/revolution-sampled impulse signal synchronized with the tool rotation is generated by a laser displacement sensor fixed with spindle, which is then interpolated to achieve 1/tooth-sampled signals. The experiment setup for Case 2 is shown in Fig. 2. The cutting forces and sound pressure signals are processed offline in time domain and frequency domain for chatter detection.

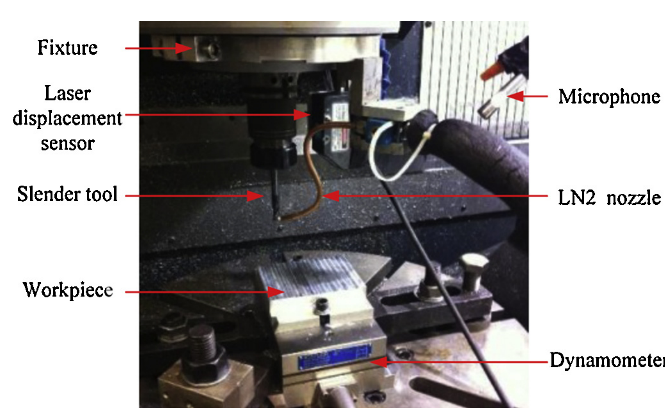

Fig. 2. Experiment Setup for cutting tests to verify the predicted SLDs.

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