

TOOL WEAR EVALUATION USING A CONSTRAINED-MOTION DYNAMOMETER

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ABSTRACT

This paper describes in-process tool wear evaluation using a constrained-motion cutting force dynamometer (CMD). Tool condition monitoring is traditionally categorized by two approaches: direct and indirect. Direct approaches provide a quantitative wear measurement. Examples of direct measurements include the use of microscopes for visual inspection, laser beams in optical tool setting systems, and electrical resistance in contact tool setting stations. Practical limitations, such as line-of-sight obstruction, coolant interference, and access problems during machining, limit the wide-spread use of these techniques. Alternatively, indirect measurement approaches allow the tool condition to be quantified through auxiliary signals. Examples include acoustic emission, temperature, motor power and current, and cutting force. The benefit of indirect techniques is that they are more suitable for shop-floor implementation because the machining processes can be continuously monitored via sensing devices which quantify the process performance or provide information for process optimization [1].

The focus of this work is force measurement. Initial results are presented which examine the variation in wear features and cutting force as the tool wear progresses from a new tool condition to a significantly worn state.

KEYWORDS

Milling, force, milling, tool wear

INTRODUCTION

The CMD combines a flexure-based constrained-motion mechanism with a low-cost optical displacement sensor, where displacement is inferred from an optical interrupter. In this approach, a knife edge is attached to the movable platform and partially blocks the optical beam during motion caused by the milling force. The displacement is used to calculate force from the known CMD structural dynamics. The result is low-cost, high accuracy dynamic force measurement. This sensor has the added benefit of a compact footprint and fast response time (10 μ s) without the need for a supplementary amplifier [2-3]. A primary use of this low-cost technology is to evaluate tool wear during machining operations. The proposed solution is to: 1) select a standard witness sample (such as 6061-T6 aluminum) and mount it to the dynamometer; 2) determine the expected cutting force level for pre-defined axial and radial depths of cut for this sample; 3) periodically perform test cuts on the sample as the tool wears in the work material; and 4) alert the machinist that a tool change is required when the force grows above a pre-selected level.

TOOL WEAR VALIDATION

To demonstrate this concept, preliminary cutting tests were performed on a Haas TM-1 CNC vertical milling machine. An Inconel® 718 AMS 5596 workpiece was mounted in a vise and a CMD was mounted to the table with an Al 6061-T6 witness sample mounted to the moving platform. A single flute, 19.05 mm diameter, endmill was used to perform machining passes at a 1.9 mm radial depth of cut (10% radial

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immersion) and 3 mm axial depth of cut at a cutting speed of 50 m/min. The insert was uncoated carbide (Sandvik 390R-070204E-NL H13A). The cutting test cases for the Inconel® 718 work material is presented in Table 1. In-situ vibration signals were collected using the knife-edge sensor on the CMD and converted to force using the structural deconvolution procedure [2-3]. A pair of optical microscopes (DinoLite Pro-AM4137) were used to record wear features on the rake and flank face of the cutting insert during tool wear testing. The experimental setup is depicted in Fig. 1. An inductive power sensor (Powertek UPC 120V) was used to monitor spindle power consumption during the tool wear tests.

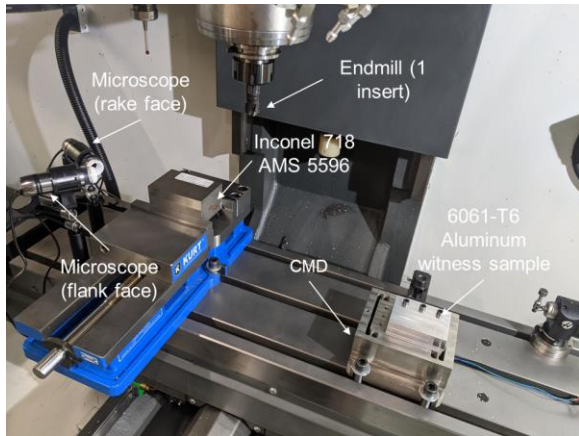


FIGURE 1. Experimental setup for tool wear measurement.

INITIAL RESULTS

To begin, a reference cutting force signal was recorded using the cutting parameters listed in Table 1. In situ vibration signals were collected using the knife-edge sensor on the CMD and subsequently converted to force using a structural deconvolution procedure [2-3]. The corresponding force is plotted in Fig. 2. For this research, the measured milling forces were parsed to capture the steady-state behavior and were then separated into 70 individual tooth impacts and averaged. This provides a compact representation of the cutting force signal over a brief time period.

Table 1. Tool description and cutting parameters for tool wear trials.

Diameter	Teeth	Insert material
19.05 mm	1	Uncoated carbide (Sandvik 390R-070204E-NL H13A)

Cutting parameters for down milling tests			
Spindle speed	835 rpm		
Feed per tooth	0.1 mm		
Axial depth	3.0 mm		
Radial depth	1.9 mm	(10% radial immersion)	

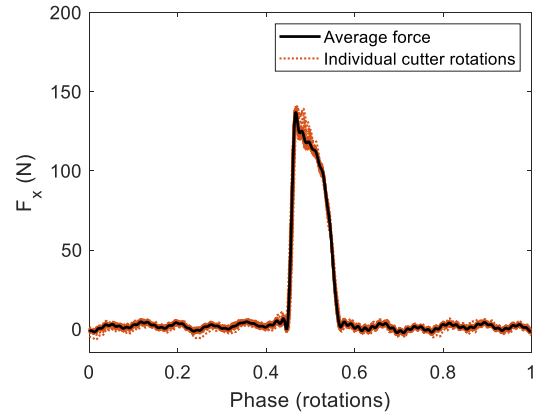


FIGURE 2. Measured cutting forces over 70 revolutions of the cutting tool (dotted red line) and their average (solid black line) for a milling operation using a new cutting insert.

The aluminum witness sample force measurement was followed by a 100 mm test cut on the Inconel® 718 work material. The normalized spindle power consumption for these tests is shown in Fig. 3. Note that there is a significant increase in power consumption between Trials 1 and 2 which is confirmed by the wear transition between the 'New insert' and the 'State 1' wear condition.

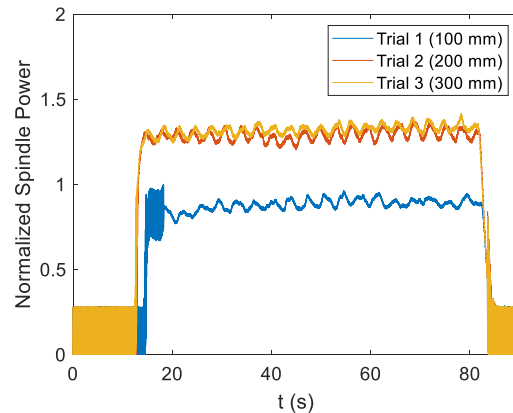


FIGURE 3. Normalized power consumption for the cutting tests in the Inconel® 718 AMS 5596 work material.

In this research, 'Trials' indicate tests performed in the Inconel® 718 work material while 'States' indicate the reference tests performed in Al 6061-T6 on the CMD. Following each cutting trial, the tool wear condition was recorded using a pair of optical microscopes. These results are shown in Fig. 4. The maximum flank wear width (FWW) was recorded and as expected, the FWW increased with cutting time.

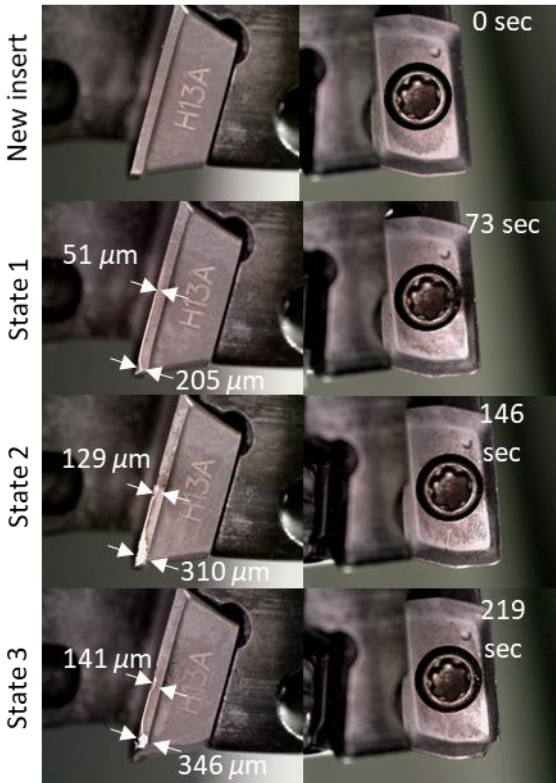


FIGURE 4. Tool wear progression. In the images, the flank face is shown by the left column and the rake face is shown by the right column.

Once the tool wear condition was measured, a cutting test was performed on the Al 6061-T6 witness sample affixed to the CMD. The purpose of these trials was to monitor the growth in cutting force levels as the tool progresses from a new to significantly, and in some cases, catastrophic wear levels. The normalized spindle power for the Al 6061-T6 witness sample is shown in Fig. 5. Traditionally, spindle power measurements are used to classify the tool wear condition. In this case, there is not a clear difference between the nominal reference force measurement (New insert) and subsequent wear states (States 1-3). This is expected since the power consumption required for Al 6061-T6 material removal

considerably smaller than for the same cutting parameters in the Inconel® work material.

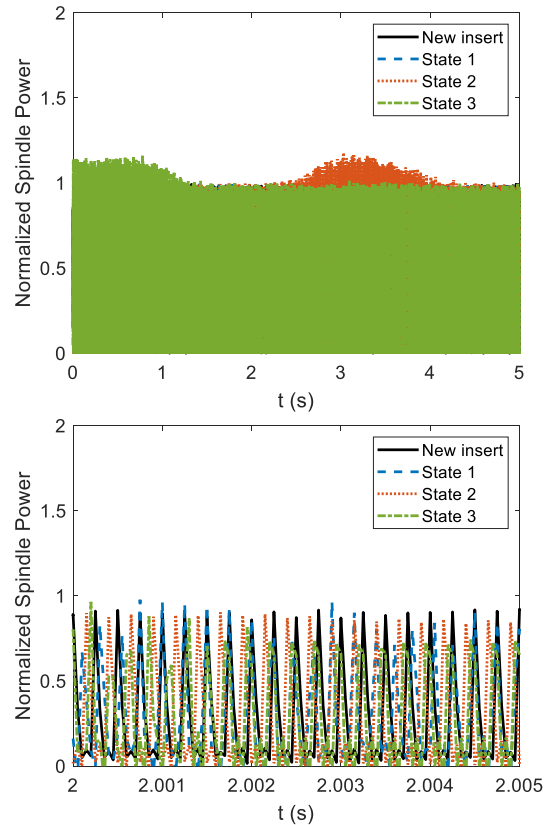


FIGURE 5. Normalized power consumption for the cutting tests on the Al 6061-T6 witness sample work material. These are indicative of the wear states in Fig. 4.

Finally, the averaged CMD cutting forces for unidirectional trials are presented for the various levels of tool wear progression, Fig. 6. Note that the cutting force signature varies depending on the tool wear condition, Fig. 4. In this case, the cutting force signature is slightly increasing with increased tool wear. In many instances, a tool is considered worn once a FWW of 300 μm is achieved. As shown by Figs. 4 and 6. The various 'States' demonstrate the subtle variability in cutting forces which are not detectable in the respective spindle power measurements; see Fig. 5.

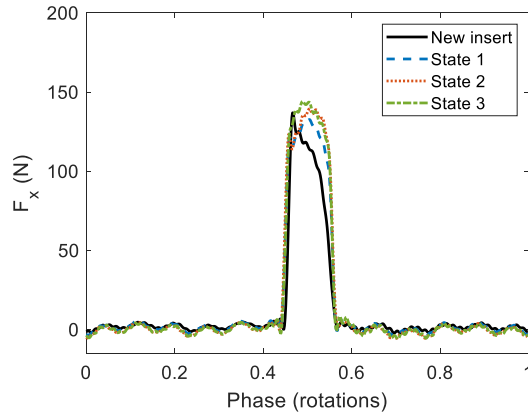


FIGURE 6. Variation in cutting force with tool wear progression in the Al 6061-T6 witness sample work material. The state levels are described by the images in Fig. 4.

FUTURE WORK

Follow-on efforts will focus on performing additional tool wear trials in various work materials including low-carbon steel alloys, titanium alloys, and Inconel® alloys. As noted previously, the research methodology is to: 1) select a standard material sample (such as 6061-T6 aluminum) and mount it to the dynamometer; 2) determine the expected cutting force level for pre-defined axial and radial depths of cut for this sample; 3) periodically perform test cuts on the sample as the tool wears; and 4) alert the machinist that a tool change is required when the force grows above a pre-selected level. The resulting cutting force signals are considered digital signatures which can identify wear features and expected cutting forces in real-time which can reduce the risk of scrapped parts, cyber-intrusion, and operator/programmer error.

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